

4 Fuels

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4.1 Automotive Diesel Fuels

4.1.1 Introduction

When Rudolf Diesel developed the first auto-ignition combustion engine at the close of the nineteenth century, he realized that gasoline's resistance to auto-ignition made it unsuitable as fuel. Comprehensive tests with various fuels revealed that so-called middle distillates were clearly more suitable. These are components that evaporate when crude oil is distilled at higher temperatures than gasoline. Until then, their potential uses had only been limited. In those days, they were typically used as lamp oil and as an additive to city gas, whence the still common designation of middle distillates as "gas oil" originates, which is still a standard customs designation.

Despite many technical problems at first, its better efficiency and the initially lower costs of diesel fuel production led to the diesel engine's commercial success. For a long time, diesel fuel was a byproduct of gasoline production.

In principle, auto-igniting engine combustion may employ widely differing fuels, provided they are highly ignitable enough and the engines and fuels are matched to each other (diesel fuels for road engines and residual oils for marine engines). Among other things, increasing demands on operational safety and exhaust and noise emissions have generated additional quality factors for diesel fuel for road vehicles, e.g.

- cleanliness,
- oxidation stability,
- flowability at low temperatures,
- lubrication reliability and
- low sulfur content.

Present day diesel fuels are specified just as precisely and strictly as gasoline. Partially contradictory requirements, e.g. ignition quality and winter capability or lubricity and low sulfur content, increasingly necessitate the use of additives.

Distinctly different fuels are basically used for the many applications for auto-ignition engines in road vehicles, locomotives or ships for economic reasons. Engineering measures can match particular engines to the different fuels.

A trend toward maximally standardized fuel is increasingly discernible on the global diesel vehicle market (cars and commercial vehicles). In fact, differences throughout the world are sometimes considerable. Gasoline engines and gasoline continue to have broad influence in the USA. Nonetheless, a trend toward advanced diesel cars and accordingly adapted diesel fuels can even be detected in the USA of late.

Unlike gasoline, usually only one grade of diesel fuel was formerly available for road traffic. Diesel fuels of differing grades, e.g. so-called truck diesel or premium diesel, have only recently also started being marketed in some countries with large populations of diesel vehicles.

Diesel fuels are still primarily produced from petroleum. Qualitatively high-grade components (with high ignition quality) have also been being produced from natural gas of late. Renewable raw material components (biofuel components) are blended with diesel fuel in low concentrations in some countries, e.g. in Germany since 2004 (DIN EN 590 [4-1]) and as a mandatory blend required by law since January 1, 2007.

4.1.2 Availability

As presently used throughout the world, diesel fuel is obtained almost exclusively from crude oil/petroleum. Reserves of some 150 billion tons of petroleum are exploitable at this time. However, this amount is dependent on the technology available, which has advanced dramatically, and on the capital available for exploration and extraction. The more crude oil costs on international markets, the more capital can be raised for exploration, development, production and transport. At the same time, this also increases the opportunities for alternative and hitherto uneconomical raw materials and manufacturing processes. The ratio between annual extraction and definitely exploitable reserves is a parameter that measures availability. At present, it is assumed that the reserves will last approximately 40 years.

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Crude oil deposits and consumption are distributed very unevenly throughout the world. Most reserves lie in the Middle East. Current scenarios assume the production of petroleum will peak in the twenty-first century. Only the timeframe and the maximum producible quantity are in dispute, depending on the particular scenario [4-2]. The synthesis of alternative fuels from natural gas and renewable raw materials is of particularly great interest (see Sects. 4.2 and 4.4).

While worldwide consumption of petroleum products including diesel fuel will initially continue to rise, more intelligent utilization will cause consumption to decline in classic industrial nations. Approximately 200 million tons of diesel fuel were consumed in Europe in 2008.

4.1.3 Production

The yield from classic production of diesel fuel by distilling crude oil (Fig. 4-1) varies depending on the crude oil used (light, low viscosity or heavy, high viscosity) (Table 4-1).

Diesel fuel is produced from middle distillates. Along with simple atmospheric and vacuum distillation, a whole raft of

other methods (thermal or catalytic cracking, hydrocracking) also exist, which increase both the yield from the crude oil and/or the quality of the components of the diesel fuel produced (Fig. 4-2).

Every cracking process breaks up high boiling crude oil fractions and converts them into lower boiling hydrocarbons. Thermal cracking (visbreaker, coker) solely uses high pressure and high temperature. A catalyst is additionally present in catalytic cracking. As a result, the finished product's composition (molecular structure) can be controlled better and fewer unstable hydrocarbons form. Hydrocracking allows maximum flexibility in terms of the yield structure (gasoline or middle distillate). In this process, hydrogen (obtained from the catalytic reformer in gasoline production) is fed to the feedstock obtained from distillation at high pressure and high temperature. This process significantly reduces hydrocarbons with double bonds, e.g. olefins and aromatics, which are less suitable for diesel fuels.

Desulfurization is another important process. Depending on its provenience, crude oil contains varying quantities of chemically bonded sulfur. Concentrations between 0.1 and 3% are typical (Table 4-2).

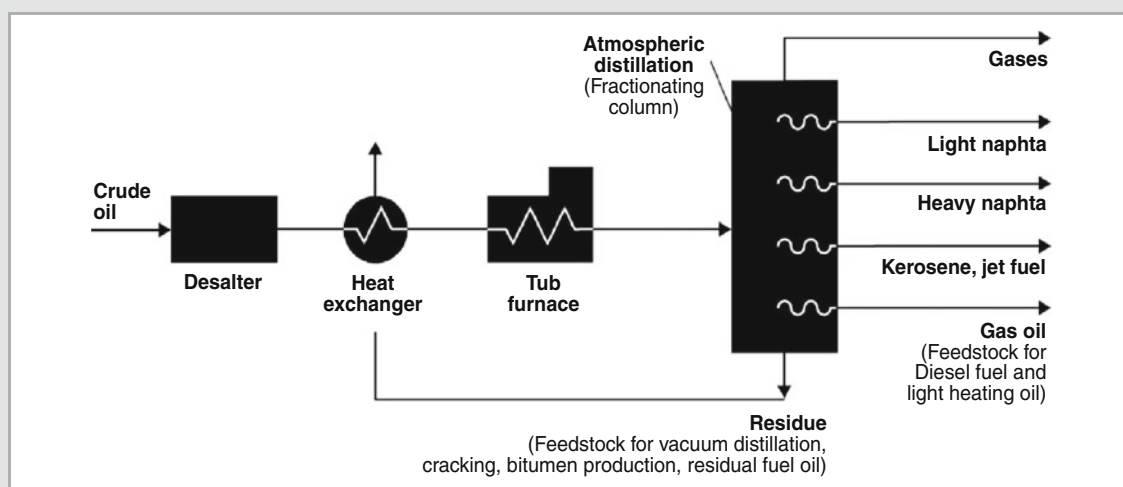


Fig. 4-1 Simplified schematic of a distillation plant

Table 4-1 Percentage distilled yield of various crude oils

Crude oil type	Middle East Arabia Light	Africa Nigeria	North Sea Brent	South America Maya
Liquefied gas	<1	<1	2	1
Naphta (gasoline fraction)	18	13	18	12
Middle distillate	33	47	35	23
Residual oils	48	39	45	64

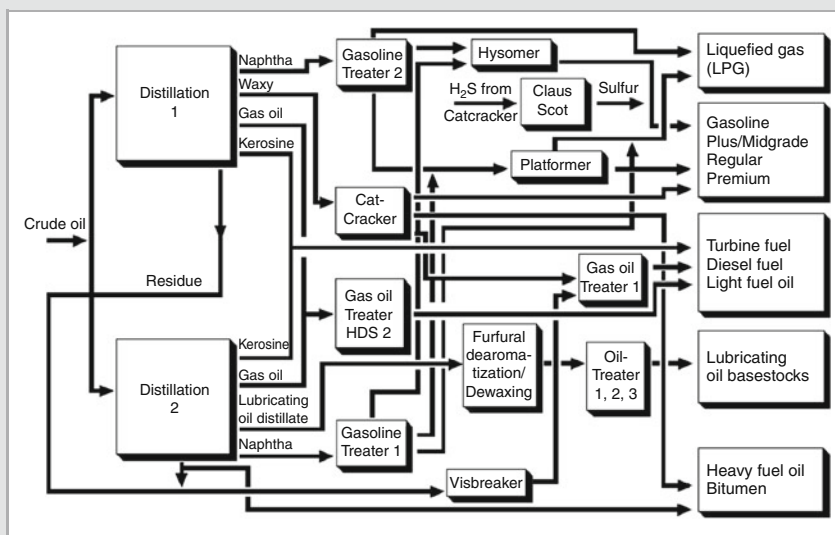


Fig. 4-2
Simplified schematic of an oil refinery

Extremely effective desulfurization is required to obtain the low sulfur content stipulated for diesel fuel (e.g. the EU only still allows sulfur-free fuels, their actual limit being a maximum of 10 ppm of sulfur). To this end, hydrogen-rich gas from a catalytic reformer is fed to the feedstock, e.g. from crude oil distillation, and conducted to a catalyst after being heated (Fig. 4-3). In addition to the desulfurized liquid phase (diesel fuel components), hydrogen sulfide is produced as an intermediate product from which a downstream system (Claus process) produces elementary sulfur.

Depending on the crude oil used and the refinery systems available, diesel fuel is produced from various components so that the product is a high grade fuel that is stable for engines in conformity with the quality requirements for summer and

winter fuels stipulated in the standards. Common components from atmospheric and vacuum distillation are:

- kerosene,
- light gas oil,
- heavy gas oil and
- vacuum gas oil (basically as feedstock for downstream cracking processes).

Furthermore, components with names corresponding to their production process are also employed. While components from distillation have differing compositions that depend on the crude oil utilized, the composition of components from cracking largely depends on the process (Table 4-3).

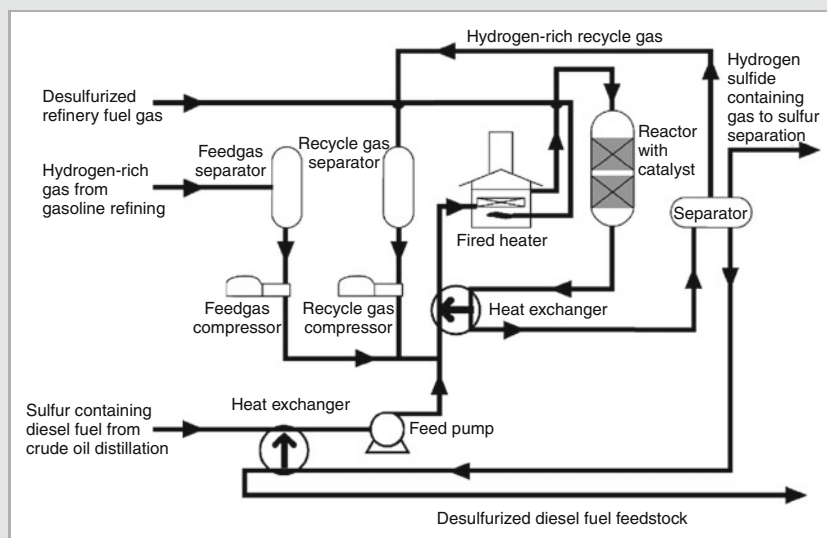
Good filterability at low temperatures is usually the distinctive feature of low boiling components and components with higher aromatic contents (e.g. kerosene). Therefore, their concentration is increased in winter. However, their ignition quality is lower. High boiling components with low aromatic content (e.g. heavier gas oils) have higher ignition quality but poorer filterability in winter. Thus, their use must be reduced in winter. Where necessary, ignition improvers can compensate for winter fuels' potential loss of ignition quality (see Sect. 4.1.5).

Once fuels are blended from the basic components, special metering units blend in additives to obtain the standardized level of quality (low temperature performance, ignition quality and wear protection) or a specific brand's properties (injection nozzle cleanliness and foam inhibition).

Fuels with quality levels that significantly exceed the standard are produced by specially selecting the components and, of late, also by using synthetic components such as gas-to-liquid (GTL) from Shell Middle Distillate Synthesis (SMDS).

Table 4-2 Typical sulfur contents of some crude oils

Provenience	Designation	Percentage sulfur content by weight
North Sea	Brent	0.4
Middle East	Iran heavy	1.7
	Arabia light	1.9
	Arabia heavy	2.9
Africa	Libya light	0.4
	Nigeria	0.1 – 0.3
South America	Venezuela	2.9
Russia		1.5
Northern Germany		0.6 – 2.2

**Fig. 4-3**

Simplified schematic of diesel fuel desulfurization

Table 4-3 Composition of diesel fuel components produced in various processes

Diesel Fuel Components	Paraffins	Olefins	Aromatics
"Straight run" distilled gas oil	Variable: middle to high	Variable: low to very low	Variable: middle to low
Thermally cracked gas oil with hydrogenation	High	Very low	Low
Catalytically cracked gas oil	Low	None	High
Hydrocracker gas oil	Very high	None	Very low
Synthetic gas oil (SMDS)	Very high	None	Very low to none

This process synthesizes a diesel fuel component with very high ignition quality (a cetane number of roughly 80) from natural gas.

Synthetic diesel fuels are nothing new. The Fischer-Tropsch process was utilized during the Second World War to produce diesel fuel from coal. However, the low price of crude oil for many years made this process uneconomical. Developments in the synthesis of fuels from renewable raw materials have better prospects for commercial success at present. Unlike the "biodiesel" from plant seeds (fatty acid methyl ester or FAME) currently in use, future fuels will much more likely be produced from entire plants or even organic residues.

Low concentrations of FAME are presently employed as a blending component in commercial diesel fuel. The EU is aiming for a concentration equivalent to 6.25% of the fuel's energy content to reduce CO₂ emissions. However, this concentration is not yet achievable because of restrictions on availability. FAME from certain regions is unacceptable because its production endangers indigenous rain forests.

4.1.4 Composition

Crude oil and the fuels obtained from it are a mixture of different hydrocarbon compounds that may roughly be divided into paraffins, naphthenes, aromatics and olefins. Other elements, e.g. sulfur, are present in very low concentrations and must be removed as far as possible during fuel production.

The potential range of variations of individual hydrocarbons increases as the boiling range increases. While the lightest energy source, natural gas, only consists of very few and precisely defined hydrocarbons, basically methane, gasoline contains more than 200 various hydrocarbons and diesel fuels even significantly more because of the frequently present combination of types of hydrocarbons described below. Aromatics have the greatest variety of paraffinic or olefinic side chains. Hydrocarbons with approximately 10–20 carbon atoms are present in diesel fuels' boiling range since it is standardized.

Unlike spark ignited gasoline engines, diesel engines need hydrocarbons that facilitate good auto-ignition at high pressures and high temperatures. These are primarily normal paraffins.

Normal paraffins are chain-like hydrocarbons with a simple carbon bond. They represent a subgroup of saturated hydrocarbons (alkanes), the term saturated referring to the chemical bonding of hydrogen. The simple carbon bond in a paraffin molecule produces the maximum potential (saturated) hydrogen content. Normal paraffins are usually present in crude oil in high concentrations. However their poor flow characteristics when cold (paraffin separation) is disadvantageous for vehicle operation. Flow improvers (see Sect. 4.1.5) in modern fuels can compensate for this. Cetane $C_{16}H_{34}$ is one example (Fig. 4-4). Unlike normal paraffins, branched isoparaffins with identical empirical formulas are unsuitable for diesel engines because of their high resistance to auto-ignition (e.g. isocetane with a cetane number of 15,

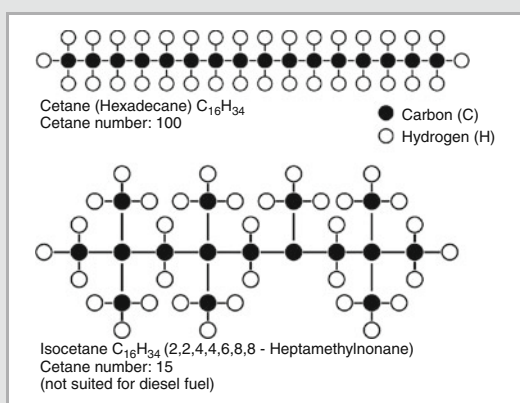


Fig. 4-4 Examples of paraffins

see Fig. 4-4). The molecules become more unstable as their chain length (molecule size) increases and thus their ignition quality increases (Fig. 4-5).

Naphthenes (Fig. 4-6) are cyclic saturated hydrocarbons (a simple bond between the carbon atoms in the molecule). Present in crude oil in varying quantities, naphthenes are produced by hydrogenating aromatic middle distillates. Naphthenes produce good low temperature performance in diesel fuel but only a medium cetane number (yet higher than aromatic hydrocarbons).

Olefins (alkenes) are simple or polyunsaturated, chain-like or branched chain hydrocarbons. While their cetane numbers are lower than those of n-paraffins, they are still quite high. For instance, the n-paraffin cetane $C_{16}H_{34}$ has a cetane number of 100, yet 1-cetene $C_{16}H_{32}$, a simple unsaturated olefin with the same number of carbon atoms, has a cetane number of 84.2. Unlike the short chain olefins used in gasoline, the simple double bond in long chain diesel fuel olefins only slightly influences physical properties and combustion performance.

Aromatics are cyclic hydrocarbon compounds in which the carbon atoms are alternately double bonded with one another, e.g. benzene, a compound not found in diesel fuel though because of its boiling point of 80°C . A distinction is generally made between mono, di, tri, and tri+aromatics based on the number of aromatic ring systems. Figure 4-7 presents a few examples relevant for diesel fuel. Since their boiling range is approximately $180\text{--}370^{\circ}\text{C}$, a large number of the most widely varying aromatic compounds may be present in diesel fuel. Predominantly monoaromatics with variously configured side chains (approximately 15–25% by weight) are present in conventional diesel fuels. Diaromatics account for approximately 5% by weight and triaromatics and higher polyaromatics usually make up less than 1% by weight.

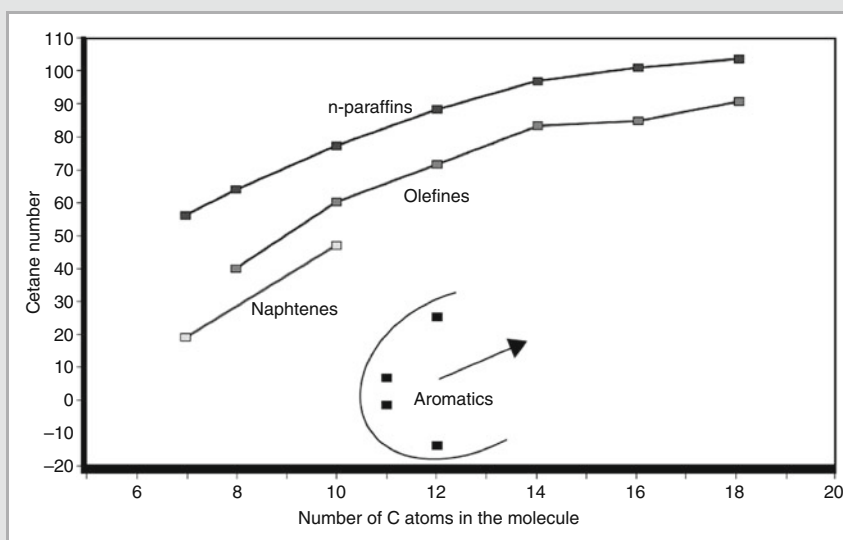


Fig. 4-5
Cetane numbers rise as molecule size increases

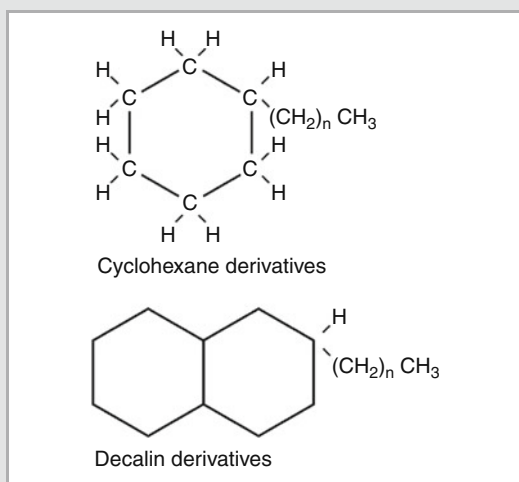


Fig. 4-6 Examples of naphthenes in diesel fuel

The properties of monoaromatics with paraffinic side chains vary. While aromatic properties (e.g. high solubility of other products and low cetane number) are dominant in molecules with relatively short side chains, molecules with long side chains have properties that make them behave more like paraffins. Polynuclear aromatics and their derivatives (see Fig. 4-7) are undesired in diesel fuels because of their poor ignition quality. They also cause increased particulate emission and are therefore limited to a maximum of 11% in the European standard EN 590 in force since 2004. The actual concentrations are usually significantly smaller. One reason is that the standardized method of analysis (high pressure liquid chromatography or HPLC) detects entire molecules including their paraffinic side chains. Thus, the real content of aromatic rings is significantly lower. Fatty acid methyl esters (FAME) appear in low concentration. (For the properties of FAME, see Sect. 4.2 Alternative Fuels.)

4.1.5 Diesel Fuel Additives

The production of modern standard diesel fuels is all but impossible without additives. The partly conflicting properties of the individual components (molecular groups) must frequently be equalized by additives to satisfy the high requirements for operational safety, rate of heat release and exhaust emission throughout an engine's entire service life. This has undergone a definite change in recent years. As a rule, more varieties and quantities of diesel fuels than gasolines are additized. With the exception of antifoaming agents, all additives consist of purely organic compounds. Described in more detail below, the most important groups of additives, are:

- flow improvers and wax anti-settling additives that improve winter capability,

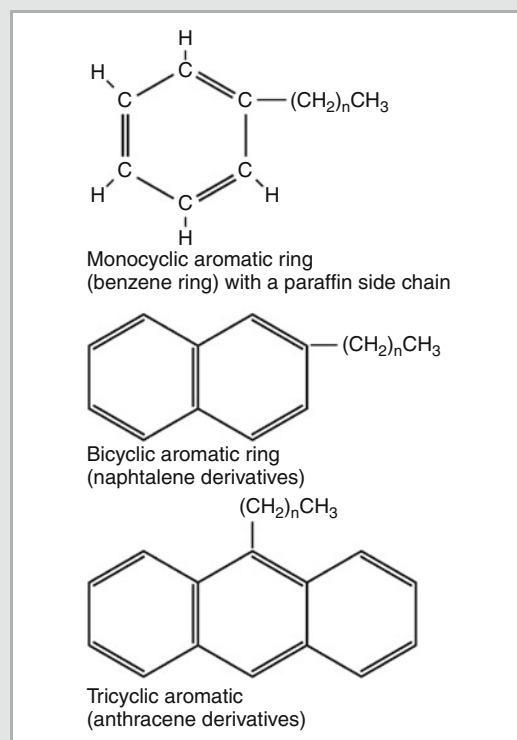


Fig. 4-7 Examples of aromatics in diesel fuel

- ignition improvers that shorten ignition delay and improve combustion performance,
- anti-wear additives that protect injection nozzles and pumps;
- antifoaming agents that prevent foaming and spilling when pumping fuel,
- detergent additives that keep injection nozzles and fuel systems clean,
- anti-corrosion additives that protect fuel systems and
- antioxidants, dehazers and metal deactivators that improve fuels' storage stability.

Odor masking agents are also used occasionally. Antistatic additives are used during manufacturing and subsequent redistribution (logistics) to the extent they are necessary to prevent electrostatic charging at high pumping rates. The use of biocides to prevent fungus infestation on tank bottoms in the water/fuel phase may be foregone when fuel distribution systems are serviced regularly.

4.1.5.1 Flow Improvers and Wax Anti-settling Additives (WASA)

Flow improvers and wax anti-settling additives make it possible to utilize paraffinic components with high cetane numbers in winter, yet limit low temperature performance.

While flow improvers cannot inhibit the formation of paraffin crystals, they can however reduce their size and prevent them from coalescing.

Typical products are ethyl vinyl acetates (EVA). On their own, flow improvers can drop the CFPP (cold filter plugging point) below the cloud point by more than 10°C . The CFPP can be lowered even further by additionally using WASA. This simultaneously reduces the sedimentation of paraffin crystals when fuel is stored below its cloud point for a long time (Figs. 4-8, 4-9, 4-10 a: formation of paraffin crystals in fuel, b: fuel sample in a glass flask).

These (usually prediluted) cold flow additives must be meticulously worked into still warm fuel at the refinery. Subsequent blending into cold fuel in a vehicle tank is usually ineffective.

4.1.5.2 Ignition Improvers

Ignition improvers facilitate an economical increase of the cetane number with a correspondingly positive influence on combustion and exhaust emission. Organic nitrates are the active ingredients. Ethyl hexyl nitrate has especially proven itself as a commercial ignition improver.

4.1.5.3 Anti-wear Additives

Also known as “lubricity additives”, these products became necessary when low-sulfur and sulfur-free diesel fuels were introduced. Diesel fuels lose their natural lubrication properties when hydrogenated to remove sulfur compounds. Fatty acid derivatives are typical products and were also already used earlier in aircraft turbine fuels.

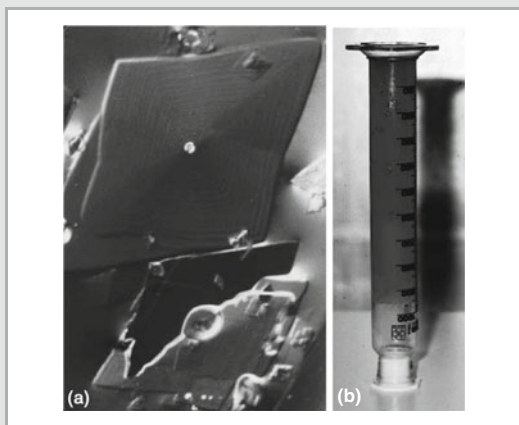


Fig. 4-8 Diesel fuel with flow improvers at -10°C : Solid, unpumpable (the glass flask is upside down)

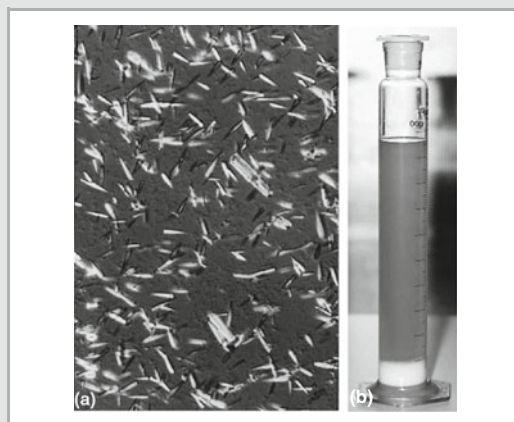


Fig. 4-9 Diesel fuel solely with flow improvers at -22°C : Paraffin crystal sedimentation



Fig. 4-10 Diesel fuel with flow improvers and wax anti-settling additives at -22°C : No paraffin crystal sedimentation

4.1.5.4 Antifoaming Agents

Antifoaming agents assure easy refueling and safe automatic shutoff of the fuel nozzle at a gas station without the spilling frequently encountered earlier and thus lower environmental pollution at gas stations. Extremely low concentrations of silicon fluids are employed. They are also used in engine oils to prevent foaming in the crankcase (Fig. 4-11).

4.1.5.5 Detergent Additives

Diesel fuels can form carbonaceous deposits in injection nozzles and thus alter the injection characteristic while adversely influencing the combustion cycle and exhaust

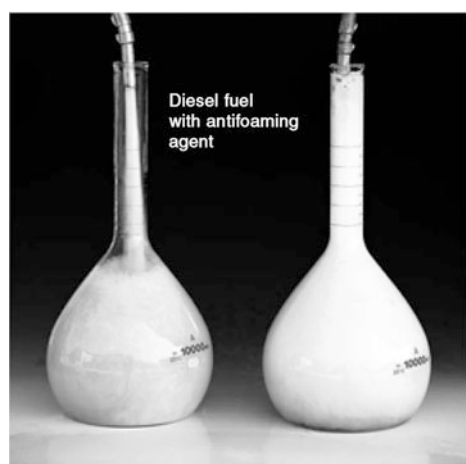


Fig. 4-11 Fuel with antifoaming agents foams less when pumped

emission. A whole series of complex organic compounds is capable of preventing nozzle coking. The active ingredients continuously have to be adapted to injection technology. Developments of new additives necessitate elaborate tests in complete engines, preferably under realistic operating conditions. Suitable detergent additives are derived from groups of amines, amides, succinimides and polyetheramines for example. Requirements for “cleanliness” and a diesel fuel’s detergent effect keep increasing as advances in diesel engine development continually increase injection pressures while reducing the size of nozzle holes

4.1.5.6 Corrosion Protection

Anti-corrosion additives are particularly necessary when small quantities of water have infiltrated the fuel, e.g. condensation during longer downtimes (Fig. 4-12). Polar molecular groups of esters or alkenoic succinimide acids build up a monomolecular protective coating on metallic

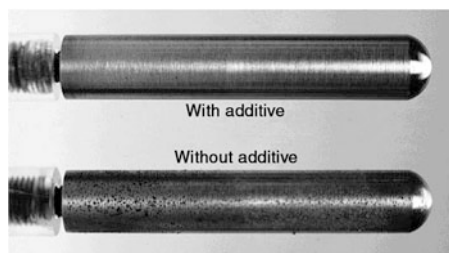


Fig. 4-12 Effect of anti-corrosion additives in a lab test

surfaces and prevent direct contact with water and acids (Fig. 4-13).

4.1.5.7 Antioxidants, Dehazers and Metal Deactivators

These additives are primarily used to improve fuel storage stability. Initially, they do not directly influence a fuel’s engine performance at all. However, they prevent fuel deterioration over long periods and thus ensure a fuel’s filterability is good and deposits are minimal after extended vehicle downtimes. They were especially necessary in fuel components from thermal and catalytic cracking plants because fuel components from these plants had higher contents of unstable hydrocarbons. Antioxidants prevent oxidation and polymerization. In part, dehazers are required to facilitate rapid settling of finely dissolved water particles. Metal deactivators prevent catalytic effects of metals on fuel ageing. Now more advanced, the hydrogenation of diesel fuel (hydrocracking, desulfurization, limitation of polynuclear aromatics) has caused these kinds of additives to lose their importance.

4.1.6 Quality Requirements

In and of themselves, diesel engines seemingly make comparatively small demands on fuel quality and, unlike spark ignited engines, even allow operation with fuels with extremely widely varying properties, e.g. residual fuels in low speed marine diesel engines. However, other than in cars and trucks, the fuel is cleaned and heated on board before being fed to the engine. Qualitatively better fuel for starting and operating an engine is also frequently available in more environmentally sensitive regions.

Barring filtering for sporadically potential impurities, fuel preparation is impracticable in road vehicles. What is more, road vehicle fuel systems and engines must operate under extremely variable conditions. This alone necessitates stricter fuel quality requirements.

Unlike gasoline engines that can be destroyed when fuel has inadequate detonation limits, diesel engines also run on fuels with lower ignition quality, albeit not well. Diesel engines are expected to deliver optimal results with respect to power, consumption, noise, exhaust emission, etc. under all conditions. However, an engine can only be successfully optimized when the interaction of the fuel and combustion system is painstakingly matched and the fuel is specified relatively narrowly. Hence, any deviation from one of the fuel properties that influences optimization generates more or less substantial disadvantages in engine performance. Therefore, the stability and narrowest possible toleration of the fuel properties are just as important for diesel engines as the absolute values and the properties of the fuel.

While great importance has always been attached to the quality of gasoline, this was not the case for diesel fuels for a

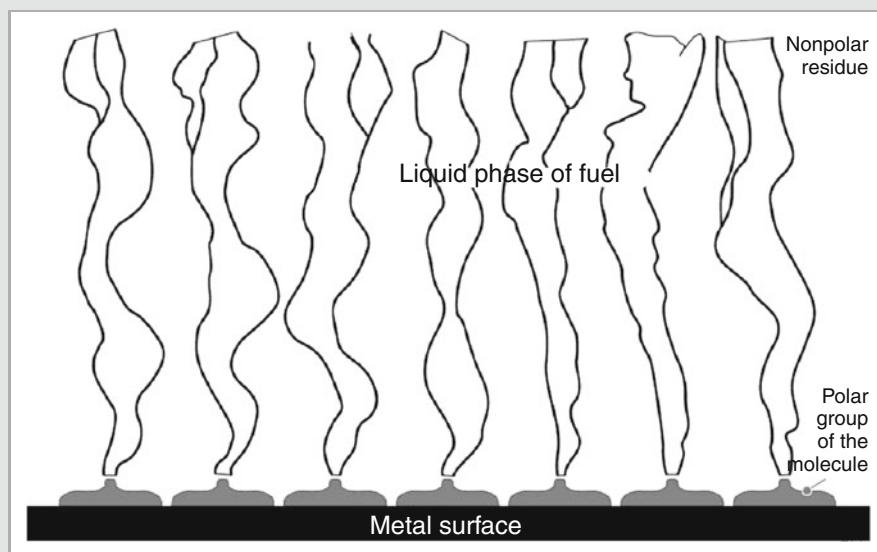


Fig. 4-13
Function of anti-corrosion
additives (monomolecular
protective coating)

long time. The cetane number was only considered important for cold starts. Inadequate cold flow properties made diesel operation a problem on cold days. Boiling characteristics were virtually unrestricted. The sulfur content was high. Additives were unknown. Purity was not particularly high. Since the quality of diesel fuel is now known to influence an engine's exhaust, noise, drivability and service life, diesel fuel quality has gained the attention it is due in large parts of the world.

In the past, quality differed considerably throughout the world. Even in such a highly industrialized country as the USA, diesel fuel and the network of filling stations was largely unsuited for cars and consumers did not accept diesel cars at first.

Historically, the quality of diesel fuel was initially largely dependent on the crude oil processed since practically only distillates were available. Quality also varied accordingly. As cracking plants that produce gasoline increased around 1970, the components they produced, which were unsuitable for gasoline because of their high boiling range, also began steadily accumulating. Since intensive hydrogenation was not yet available, the mineral oil industry increasingly considered blending these components into diesel fuel at that time. These components' aromatic and olefinic constituents would have degraded diesel fuel quality though. However, these ideas were not pursued any further because of resistance from the engine industry as well as mounting quality requirements ensuing from limits on exhaust emissions. On the contrary, diesel fuels were additized against deposits and foaming and even to improve odor. Ignition improvers were employed and, above all, cold drivability based on climatic conditions was guaranteed in winter, e.g. at -22°C in Germany.

In the meantime, many countries have additional types of diesel fuel with significantly improved properties, which, among other things, even lower untreated emissions. One example and trendsetter is Sweden's "city fuel".

While lawmakers formerly only regulated maximum sulfur content, regulations corresponding to those for gasoline are now in force in the European Union. In addition, it has an act on flammable liquids (flash point), a customs tariff and fuel oil designations.

4.1.7 Fuel Standards

Standards that regulate minimum requirements are indispensable for communication between engine manufacturers and fuel producers, retailers and consumers. Here too, much has changed positively in terms of suitability and environmental compatibility. While every country formerly had its own specifications, the standard EN 590 has been in effect for all of Europe since 1993 [4-1] and applies to all the countries represented in the European Committee for Standardization (CEN). However, every country may enact (additional) individual regulations in a national appendix. Special classes specifying flow characteristics during cold weather with correspondingly low CFPP (cold filter plugging point) and CP (cloud point) were implemented for arctic countries. EN 590 has largely defined every relevant fuel parameter at a relatively high level of quality. The most recent version from 2008 is currently undergoing the process of adoption (Table 4-4). Section 4.1.8 outlines the individual parameters.

Regular revision of the standards and the test methods applied guarantees the inclusion of new or modified criteria

Table 4-4 Diesel fuel quality: Minimum requirements according to DIN EN 590: 2008–2009

	Unit	Minimum requirements		Test procedure
Density at 15°C	kg/m ³	Moderate climate 820–845	Arctic climate 800–840 or 845	EN ISO 3675 EN ISO 12185
Cetane number		Min. 51	Min. 47, 48 or 49	EN ISO 5165 EN 15195
Cetane index		Min. 46	Min. 43 or 46	EN ISO 4264
Distillation: percentage recovered to 180°C to 250°C to 340°C to 350°C 95% recovered	Percent by volume Percent by volume Percent by volume Percent by volume °C	Max. 65 Min. 85 Max. 360	Max. 10 Max. 95	EN ISO 3405
Flash point	°C	Min. 55		EN ISO 2719
Viscosity at 40°C	mm ² /s	2.00–4.50	1.2; 1.4 or 1.5–4.0	EN ISO 3104
Filterability / CFPP				EN 116
Class A	°C	Max. +5		
Class B	°C	Max. 0		
Class C	°C	Max. –5		
Class D	°C	Max. –10		
Class E	°C	Max. –15		
Class F	°C	Max. –20		
Class 0	°C		Max. 20	
Class 1	°C		Max. 26	
Class 2	°C		Max. 32	
Class 3	°C		Max. 38	
Class 4	°C		Max. 44	
Cloud point				EN 23105
Class 0	°C		Max. 10	
Class 1	°C		Max. 16	
Class 2	°C		Max. 22	
Class 3	°C		Max. 28	
Class 4	°C		Max. 34	
Sulfur content	mg/kg	Max. 10		EN ISO 20846 EN ISO 20884
Carbon residue	Percent by weight	Max. 0–30		EN ISO 10370
Ash content	Percent by weight	Max. 0.01		EN ISO 6245
Cu corrosion	Corrosion rating	Class 1		EN ISO 2160
Oxidation stability	g/m ³ h	Max. 25 Min. 20		EN ISO 12205 pr EN 15751
Total impurities	mg/kg	Max. 24		EN 12662
Water content	mg/kg	Max. 200		EN ISO 12937
Lubricity (HFRR)	µm	Max. 460		EN ISO 12156-1
Polyaromatics	Percent by weight	Max. 11		EN 12916
Fatty acid methyl ester content (FAME)	Percent by volume	Max. 5		EN 14078

for requirements. For instance, wear protection (lubricity) and limits on polyaromatics have been newly incorporated in recent years.

The test methods applied in the standard and to ongoing quality control are also based on standardized laboratory methods. By performing extensive tests in complete engines for example, working groups from the engine and petroleum industry and independent institutes ensure that the standardized methods are relevant to the application of fuel in vehicles.

EN 590 contains legal regulations from EU directives and compromises negotiated between the automotive and petroleum industries in the CEN working group TC19/WG24.

Furthermore, the German government has enacted the Fuel Quality Act [4-3] and related provisions for its implementation [4-4]. State authorities are able and required to review the conformity of fuels offered for public purchase to the standards. These efforts are aimed at ensuring that customers who purchase fuel with an EN 590 designation can be confident that the fuel is suitable for their engines and is environmentally compatible.

4.1.7.1 Worldwide Fuel Charter

In the early 1990s, diesel engine manufacturers were universally unhappy with the minimum requirements specified for diesel fuel, the unduly slow progress of international standardization and the fragmentation stemming from national differences in quality. Peugeot and Renault compiled a *Cahier des Charges* that not only contained higher diesel fuel quality specified by lab values but also a method to test the cleanliness of injection nozzles (additivation).

The automotive associations in Europe, the USA and Japan have compiled performance specifications for “good” qualities of diesel fuel. A logical consequence of globalization was the drafting of a Worldwide Fuel Charter by the world’s automotive associations, the fourth edition of which was published in 2006 [4-5]. It applies to both gasoline and diesel fuel and contains four categories for differently developed markets, which are defined by the requirements of emission control legislation.

The Fuel Charter outlines laboratory and engine test methods with related limits. Category 4 requires sulfur-free fuel, i.e. with a maximum sulfur content of 5–10 ppm. Commercially available diesel fuels now fulfill a large number of stipulated quality criteria.

4.1.7.2 Reference Fuels

Reference measurements, legal approval, engine developments, engine oil tests, etc. require defined reference fuels. Naturally, these can only be defined when everyone involved collaborates. The Deutscher Koordinierungsausschuss (DKA)

is responsible for the development of test methods for the evaluation and development of fluids for combustion engines in Germany. The Coordinating European Council (CEC) is responsible for the same in Europe. A CEC reference fuel for diesel engine emission tests is legally stipulated. By definition, it is a weighted mean value of the European commodity.

Engine oil tests for diesel engines primarily check piston cleanliness, sludge formation and wear, which are also influenced by the fuel. Therefore, a CEC reference fuel is used in most diesel engines even for oil tests.

4.1.8 Basic Parameters and Test Methods

4.1.8.1 Ignition Quality (Cetane Number, Cetane Index)

Naturally, a fuel’s ignition quality plays a prominent role in auto-ignition engines. Prior experience has demonstrated that laboratory equipment is unable to determine it accurately enough. Rather, it can only be reliably determined in an engine, preferably a modern multi-cylinder engine. However, ignition quality is determined in standardized single cylinder engines for reasons of standardization. The CFR engine compliant with EN ISO 5165 is used worldwide. The so-called BASF engine compliant with EN 15195 is also used, mainly in Germany. The cetane number specifies ignition quality. Where the CFR engine is used, it is calculated for a fuel under test by varying the engine’s compression ratio for constant ignition delay (high fuel-ignition quality requires a drop in the compression ratio and vice versa). The air/fuel ratio in the BASF engine is varied to obtain a constant and defined ignition delay. Cetane and α -methyl-naphthalene with defined cetane numbers of 100 and 0 respectively are used as reference fuels (Fig. 4-14). By definition, a fuel that produces the same engine settings in a test engine as a mixture of 52% cetane and 48% α -methyl-naphthalene (percent by volume) has a cetane number of 52.

Fuels with insufficient ignition qualities produce greater ignition delays. This leads to poor cold starting, high pressure peaks and thus higher exhaust and noise emission.

Paraffins have high cetane numbers, while hydrocarbons with double bonds and aromatics in particular have low ignition quality. The cetane numbers of paraffins increase as the length of their chains increases, i.e. as their molecular weight and boiling point increase (Figs. 4-5 and 4-15).

EN 590 stipulates a minimum cetane number of 51. German diesel fuels have a cetane number of approximately 52 with a tendency toward higher values in summer fuels and lower values in winter fuels (because high boiling paraffins are eliminated partly to ensure safe low temperature filterability).

The ignition quality of conventional diesel fuels is adequately characterized by their cetane numbers. This is also true for fuels with ignition qualities enhanced by ignition improvers. By contrast, alcohol fuels with large quantities of

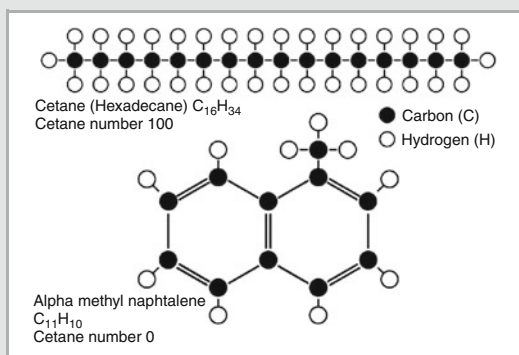


Fig. 4-14 Reference fuels for cetane number measurement

ignition improvers perform differently in a complete engine than their cetane number might lead one to expect.

Starting and noise properties and, in particular, gaseous exhaust emissions of HC and CO as well as NO_x improve in diesel engines as the cetane number increases.

High pressure and high temperature hydrogenation elevates the cetane number of refinery components. The refinery processes of hydrocracking and desulfurization are headed in this direction to some extent. Plants that produce synthetic diesel fuel components (e.g. from natural gas) for premium fuels have now become cost effective. The available quantities of such components are still limited however.

Alternatively, the cetane index may be calculated from the fuel density and boiling characteristics according to EN ISO 4264 to evaluate the ignition quality of conventional diesel fuels without measuring the cetane number. The empirical formula developed for typical commercial fuels is based on an analysis of approximately 1,200 diesel fuels. With a number of corrections, the fundamental statement asserts that the cetane number drops as density increases (i.e. the fraction of cracking products with double bonds or aromatics increases) and the cetane number increases as the high boiling components increase (the chain lengths of molecules grow).

The formula has been altered repeatedly to reflect longer-term changes in refinery structures and diesel fuel components. However, it is less suitable for individual fuel components. By the same token, it cannot specify the cetane number of fuels with ignition improvers.

The imprecision of the empirical formula (in particular the non-inclusion of fuels containing ignition improvers) and the relatively broad spread in the measurement of cetane numbers result in variations between the measured cetane number and the calculated cetane index of up to 3 units.

4.1.8.2 Boiling Characteristics

Diesel fuels consist of hydrocarbon mixtures that boil in a range of approximately 170–380°C. EN ISO 3405 defines distillation equipment and distillation conditions (among others, a variable supply of energy for a constant distillation

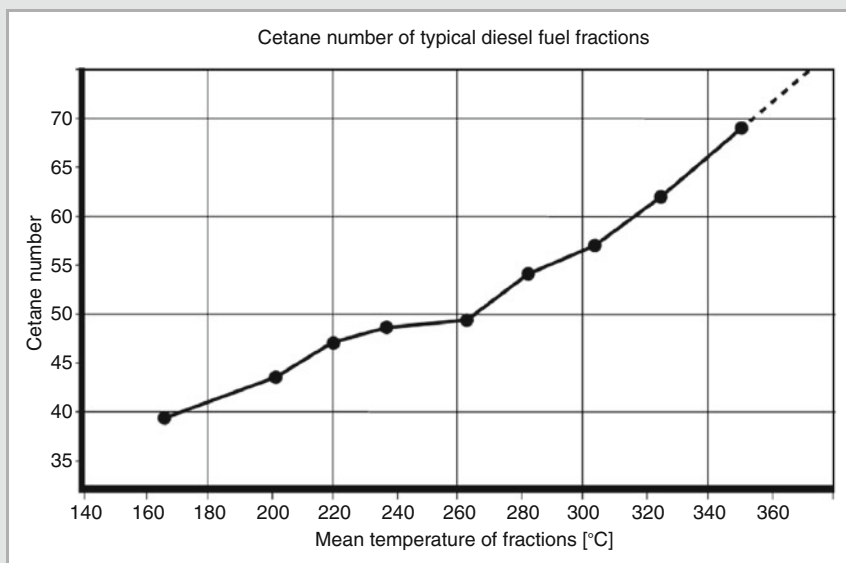


Fig. 4-15

The cetane number of typical diesel fuel fractions rises with the boiling temperature

rate of 4–5 ml/min). The method does not specify any physically exact boiling range but rather practical conditions of boiling characteristics approximating rapid vaporization. Low boiling components are partially retained when a product mixture's temperature rises, while high boiling components are already entrained. Therefore, the physically exact initial or final boiling point is lower or higher than specified. Nevertheless this standardized method is well suited for evaluating diesel fuels.

In principle, hydrocarbons outside the usual boiling range are also suitable for diesel engine combustion, e.g. marine engines run with fuels that evaporate at considerably higher temperatures. A number of other constraints (e.g. viscosity, low temperature flowability, density, ignition quality and flash point) limit the boiling range of fuels allowable for vehicle operation and fuel system design.

Therefore, EN 590 stipulates only three points that define fuel in the mid to final boiling point range (Fig. 4-16). However, the final boiling point of diesel fuels is not precisely determinable, in part because cracking processes may already commence in the distillation equipment at temperatures above 350°C when the final fuel fractions are being vaporized. This uncertainty is also the reason why EN 590 does not explicitly define the final boiling point.

Diesel engines react less critically to a fuel's boiling rate. Lowering the final boiling point has proven to enhance combustion performance and reduce exhaust emissions in high speed diesel engines. Therefore, the latest revision of EN 590 lowered the temperature for a 95% vaporized fraction from 370 to 360°C.

4.1.8.3 Sulfur Content

Crude oil already contains varying quantities of sulfur. SO₂ formation during combustion, engine oil acidification, sulfate emission, increased particulate emission and damage to exhaust gas aftertreatment systems (catalysts) make the desulfurization of diesel fuel essential. Even though road traffic contributes little directly to sulfur dioxide pollution, exhaust gas aftertreatment systems require sulfur-free fuel (S <10 ppm). The sulfur contents can be ascertained with different methods, e.g. UV fluorescence or X-ray fluorescence. EN ISO 20846 and EN ISO 20884 describe the appropriate methods for diesel fuels. The limits for the maximum allowable sulfur content have been lowered steadily. Diesel fuel's formerly higher sulfur content seriously affected engine service life. The acidic products produced during combustion caused corrosive wear, above all on the cylinder barrel and in the piston ring zone, which, in turn, caused increased oil consumption and loss of power. Cylinder wear particularly increases during stop-and-go operation. However, highly alkaline engine oils can neutralize the acidic combustion products that accrue. Reducing oil change intervals is another option when the sulfur content is higher. The EU has limited the maximum sulfur content to 50 ppm since 2005 and to 10 mg/kg (sulfur-free) since January 2009.

4.1.8.4 Low Temperature-Flowability

The hydrocarbons generally viewed as beneficial for operation in diesel engines, paraffins unfortunately frequently

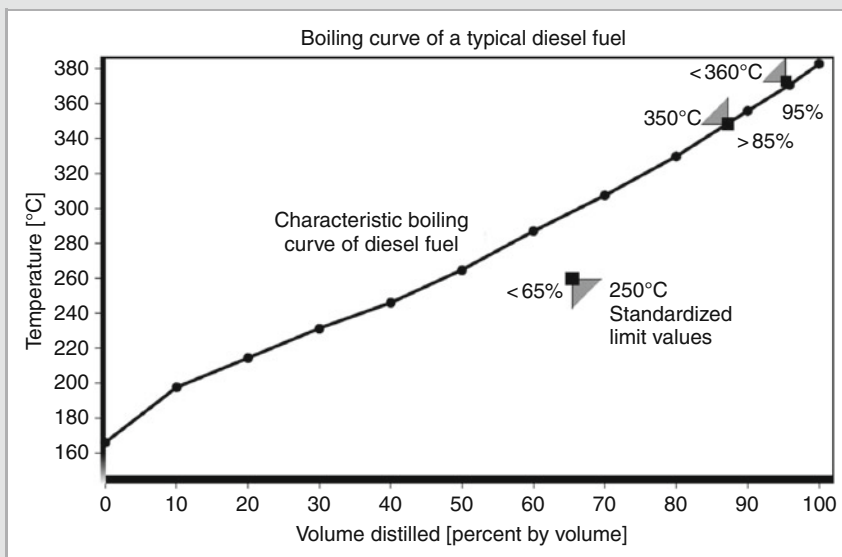


Fig. 4-16
Boiling characteristic of a typical diesel fuel

precipitate as paraffin crystals at low subzero temperatures, which coagulate and clog the fuel filter, lines and injection system and thus impede an engine's operation. Although a start is frequently still possible, the lack of fuel causes the engine to stop without suffering damage.

Diesel fuels' low temperature flowability is measured with the cold filter plugging point (CFPP), which ascertains the lowest temperature at which a diesel fuel still flows unimpeded and is filterable. EN 116 stipulates measuring this with a sieve with a mesh width of 45 μm and gauge of 32 μm at a cooling rate of approximately 1°C/min.

Fuels without cold flow additives have a CFPP just slightly below the cloud point, i.e. the start of paraffin separation. Depending on the type and quantity of additives, cold flow additives reduce paraffin crystals so that the CFPP can be lowered more than 20°C below the cloud point. The cloud point (CP) is the measured temperature at which the first crystallizing paraffins visibly cloud fuel. It is irrelevant for diesel fuel filterability in modern vehicles and therefore also not specified in DIN EN 590. CFPP values of up to approximately 15°C below the cloud point can solely be obtained by using flow improvers. Further reductions are possible by combining flow improvers and wax anti-settling additives.

EN 590 calls for low temperature resistances that correspond to ambient temperatures and are expressed by the CFPP. The values presented in Table 4-5 were selected for Germany, i.e. a Central European country. Arctic fuels require adequate filterability at lower temperatures. These fuels also have a cloud point specification with a difference of 10°C between the cloud point CP and cold filter plugging point CFPP.

The CFPP approximately describes a vehicle's operational reliability. Since the fuel contains small paraffin crystals below the cloud point and in the CFPP range, filters ought to be installed in a fuel system whenever the engine or other measures heat the filter once an engine starts. Vehicles with actively heated filters facilitate reliable operation even at temperatures lower than specified by the CFPP. The reliable operational temperature in vehicles with filters heated by engine heat approximately corresponds to the fuel's CFPP.

4.1.8.5 Density

Density is the mass of a certain volume of fuel specified in kg/m^3 at 15°C (EN ISO 3675, EN ISO 12185). Fuel density has traditionally been measured with aerometers or, more recently, on the basis of the principle of flexural vibration. A pipe bent into a U-shape is filled with a small amount of the fuel under test. The pipe is excited to vibrate and the resultant resonant frequency is measured and converted into a density value.

Diesel fuel's density increases as its carbon content increases, i.e. as the chain length of the paraffinic molecules increases and the proportion of double bonds increases

Table 4-5 Seasonal cold filter plugging point (CFPP) specification of diesel fuels according to EN 590 (in Germany)

Winter	November 16–February 28	Class F	Max. –20°C
Spring	March 1–April 14	Class D	Max. –10°C
Summer	April 15–September 30	Class B	Max. +/–0°C
Fall	October 1–November 15	Class D	Max. –10°C

(aromatics and olefins). Accordingly, an increasing hydrogen fraction in diesel fuel lowers its density. A fuel's volumetric calorific value also rises as its carbon content increases, i.e. increasing density is an indication of higher calorific value per volume. Hence, the energy supplied to an engine increases when the fuel density increases while the volume injected remains constant. Since the quantity of fuel injected in standard vehicle diesel engines is not yet controlled as a function of fuel, high fuel density in the full load range can simultaneously boost engine power and increase particulate and smoke emission. This is especially true of volume metering injection systems. Accordingly, when the same power is delivered, the volumetric fuel consumption drops as density increases. Decreasing density has the converse effect, i.e. higher volumetric consumption and less particulate emission with potential loss of power at full load. A recent revision of EN 590 lowered the maximum density from 860 to 845 kg/m^3 with the goal of reducing particulate emissions in the existing car fleet.

These correlations are only valid when fuels' combustion performance remains roughly constant. The higher hydrogen and thus energy content in synthetic (gas-to-liquid) fuel than in conventional diesel fuel manifests itself positively relative to the gravimetric calorific value.

4.1.8.6 Viscosity

Viscosity (resistance) is the capability of a flowable material to absorb stress while deforming. It is only dependent on the rate of deformation (see DIN 1342). Fuel viscosity influences the fuel delivery characteristic in delivery and injection pumps and the fuel's atomization by the injection nozzle. A distinction is made between dynamic viscosity η in $\text{Pa}\cdot\text{s}$ and kinematic viscosity ν , the latter being the quotient of dynamic viscosity and density specified in m^2/s or in mm^2/s .

The Ubbelohde capillary viscosimeter (EN ISO 3104) measures diesel fuels' kinematic viscosity by measuring the time it takes a sample quantity of 15 ml to flow through a defined capillary tube at a temperature of 40°C.

EN 590 stipulates a viscosity range of 2.0–4.5 mm^2/s for diesel fuels. Lower minimum values down to minimum values of 1.2 mm^2/s apply to arctic fuels.

Commercially available fuels have a range of 2.0–3.6 mm^2/s at the stipulated temperature of 40°C. Viscosity is usually not

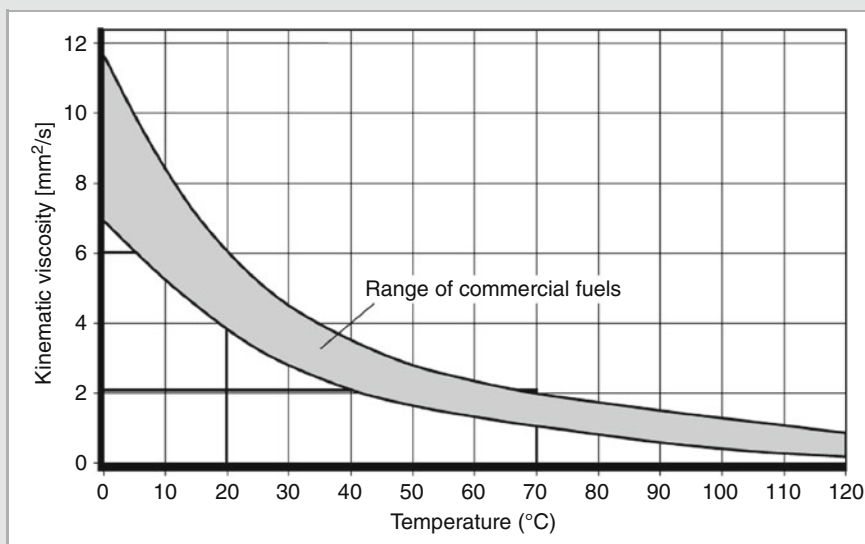


Fig. 4-17
Diesel fuel viscosity-temperature
diagram

a primary criterion in fuel production. Rather, it results from other fuel parameters.

Viscosity increases as the temperature drops and the pressure rises. For instance, the viscosity of diesel fuel doubles when the temperature drops from 40 to 20°C (Fig. 4-17) or the pressure increases to approximately 600 bar. Viscosity influences a fuel's flow and pump characteristics in a fuel system and the development of the injection spray in the combustion chamber, which is shaped by the injection nozzle. Excessively high viscosity impedes pumpability at low temperatures and causes cold start problems, while excessively low viscosity makes hot starting difficult and causes power losses at high temperatures and pump wear.

4.1.8.7 Flash Point

A liquid's flash point is the lowest temperature at normal pressure at which it vaporizes in a closed vessel in such quantity that a vapor-air mixture is produced, which external ignition can cause to ignite (as defined by EN ISO 2719). The flash point is a safety parameter. It is not important for combustion in engines.

The risk of ignition decreases as the flash points increase (in °C). A maximum of 55°C is specified for diesel fuel. A number of ordinances and technical regulations regulate the storage and transportation of inflammable liquids, the handling of hazardous substances and industrial safety. The flash point is one of the major criteria in most of these ordinances when they are applied to diesel fuel.

Gasoline has a much lower flash point (<2°C). The ingress of even small quantities of gasoline can reduce the flash point of diesel fuel below the limit of 55°C and represents a safety

hazard, e.g. when alternately transported in the same tank chambers used for diesel fuel.

The flash point limits the use of low boiling components in the production of diesel fuel. The flash point's limit is one reason why the initial boiling point of diesel fuel does not have to be specified.

4.1.8.8 Aromatics

With their cyclic and double bonded molecular structures, aromatics are basically unsuitable for diesel engine combustion because of their poor ignition quality (see Sect. 4.1.4). However, the mononuclear aromatics with longer side chains present in diesel fuels have properties similar to long chain paraffins. Benzene (without side chains), toluene and xylene (ring benzene with short side chains) have boiling points that are too low for diesel fuel and are therefore not contained in it. Given their higher boiling point, polynuclear aromatics, e.g. naphthalene (2-ring) or anthracene (3-ring), may also be present without "thinning" side chains. 4-ring aromatics boil above 380°C, i.e. above diesel fuel's boiling range, and are therefore only allowed to be present in traces.

Finding a suitable method for continuous quality control that identifies the aromatics in diesel fuel was problematic. For a number of years, the total polyaromatics have been measured with high pressure liquid chromatography and refractive index detectors in accordance with EN 12916. This determines the mass of polyaromatic ring structures including their side chains, i.e. the content of aromatic ring structures actually present is lower than detected. The content of polynuclear aromatics in commercial diesel fuels drops as the number of rings increases. Mononuclear aromatics with long side chains are now known to behave similarly to paraffins, particularly with respect to exhaust emission and particulate formation.

Polynuclear aromatics have an adverse affect and are therefore limited in EN 590 to a maximum of 11% by weight.

4.1.8.9 Purity

Purity includes the standardized criteria of carbon residue, ash content, total impurities and water content. Since diesel fuel is a high grade resource and its use in diesel engines entails strict requirements, it is supposed to be clean and pure when pumped into a vehicle's tank. It must be free of acids and solid impurities and clear at room temperature.

In conjunction with other criteria, carbon residue (according to Conradson) is a significant indicator of the formation of deposits in an injection system and combustion chamber. Hence, this residue is also limited. Carbon residue is measured by carbonizing the last 10% from the boiling analysis at low temperature according to EN ISO 10370. A maximum of 0.3% may be present. Commercially available fuels contain approximately 0.03%. Since some diesel fuel additives (e.g. ignition improvers) elevate carbon residue, only unadditized fuels ought to be investigated.

Ash content describes the content of inorganic contaminants in the fuel. It is ascertained by incinerating/ashing a fuel sample according to EN ISO 6245 and may not exceed 0.01% by weight. It is usually below the detection limit in typical commercial fuels.

Total impurities specify the total undissolved contaminants (sand, rust, etc.) in a fuel according to EN 12662. This is measured by filtering and weighing after washing with n-heptane. Twenty-four milligrams per kilogram are the permissible maximum. Values below 10 mg/kg are usually common. Higher values may cause problems, especially in winter when paraffin crystals additionally load filters that are partially clogged by contaminants.

Water is already present in crude oil and also winds up in fuel during some refinery processes. Hence, fuel is dried afterward. The amount of dissolved water decreases as the temperature and aromatics content decrease. Roughly between 50 and 100 mg/kg at 20°C, it is significantly lower than in gasoline. Two hundred milligrams per kilogram are the permissible maximum. Water content is measured by titration based on the Karl Fischer method in EN ISO 12937.

Any ingress of water in diesel fuel ought to be prevented, especially in winter, because ice crystals can quickly clog filters together with paraffin crystals.

The careful handling of diesel fuel required also entails preventing the formation of any algae, bacteria and fungi. This can usually be accomplished merely by cleaning and regularly dewatering the storage tanks in a distribution network.

4.1.8.10 Lubricity

Diesel fuels with very low sulfur content have proven to potentially cause high wear in fuel-lubricated injection pumps. This is caused not by the absence of sulfur as such

but rather by the absence of wear reducing polar substances removed during desulfurization. Additives assure the requisite lubrication reliability. This can be ascertained by a fast mechanical test using a high frequency reciprocating rig (HFRR) based on EN ISO 12156-1. The HFRR test simulates sliding wear in an injection pump by rubbing a sphere (with a 6 mm diameter) on a polished steel plate under liquid at a constant pressure at a test temperature of 60°C (Fig. 4-18). The measured flattening of the sphere produced after 75 minutes is the test result (mean wear diameter in μm). EN 590 allows a maximum wear diameter of 460 μm .

4.1.8.11 Calorific Value

A distinction is made between the gross calorific value H_o and the net calorific value H_u (now only designated as calorific value H). The gross calorific value H_o , or calorific power, is ascertained by complete combustion in a bomb calorimeter with an oxygen atmosphere of 30 bar. Carbon dioxide and potentially present sulfur dioxide are gaseous after combustion, while the steam produced condenses. Since the steam does not condense during engine combustion, the calorific power is unrealistically high for a practical evaluation of fuels. Therefore, the hydrogen content is determined in an elemental analysis and the heat of condensation from the steam produced is calculated and subtracted from the calorific power to ultimately obtain the calorific value (DIN 51900).

Calorific value is a value that results from density, boiling characteristics and fuel composition. It is not measured for the purpose of quality control during fuel production. Only fuels used for particular research and development work must be measured. Table 4-6 presents values of some typical diesel fuels. Given their higher densities (higher carbon fraction), diesel fuels have volumetric calorific values that are approximately 15% higher than those of gasolines.

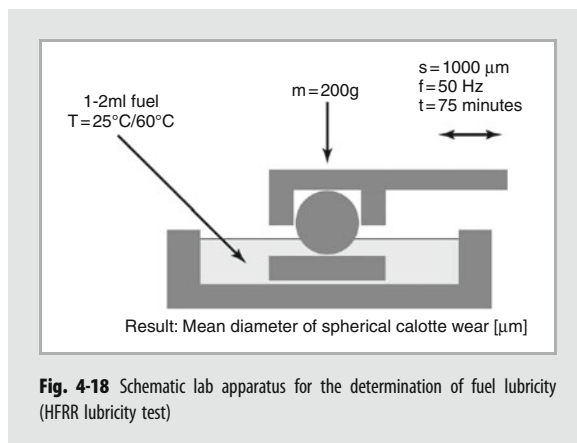


Fig. 4-18 Schematic lab apparatus for the determination of fuel lubricity (HFRR lubricity test)

Table 4-6 Calorific values and elemental analyses of commercially available diesel fuels (Source: DGMK, Hamburg)

Diesel fuel	Density at 15°C [kg/m ³]	Elemental analysis			H _o MJ/kg	H _u MJ/kg	H _u MJ/l
		C	H	O			
		Percent by weight					
A	829.8	86.32	13.18	—	45.74	42.87	35.57
B	837.1	85.59	12.7	—	45.64	42.9	35.91
C	828.3	86.05	13.7	—	46.11	43.12	35.72
Mean	831.7	85.99	13.19	—	45.84	42.96	35.73

4.1.8.12 Corrosiveness on Metals

Diesel fuel inevitably comes into contact with moisture and oxygen during its transport, storage and use in vehicles. Resultant temperature changes and condensation can corrode lines and reservoirs. Corrosion products can cause damage in a vehicle's distribution chain and fuel system including its sensitive injection nozzles.

Steel's corrosion behavior is tested according to DIN 51585. A steel rod is inserted in a mixture of fuel and distilled water (variant A) or artificial saltwater (variant B) with a 10:1 ratio for twenty-four hours at 60°C. Once the test has concluded, the formation of rust is evaluated visually. This method is used, for example, to test the effectiveness of anti-corrosion additives (see Fig. 4-12).

The corrosion of cupreous materials that come into contact with fuel (e.g. fuel pump components) is problematic for two reasons. On the one hand, components are damaged. On the other hand, dissolved copper is catalytically active and causes the formation of substantial molecular impurities in the fuel. A fuel's corrosiveness basically depends on its water content, oxygenic compounds, the type and quantity of sulfur compounds and, naturally, the anti-corrosion additive employed. A ground copper strip is brought into contact with diesel fuel at 50°C for three hours (EN ISO 2160) to test the corrosion limit stipulated in EN 590. Even under adverse conditions, additives largely protect all the metals that come into contact with fuel.

4.1.8.13 Oxidation Stability

Fuels may partially oxidize and polymerize when stored over long periods (> 1 year as strategic stocks/petroleum reserves). This can cause insoluble constituents to form and thus filters to clog later in vehicles. The chemical mechanism is the cleavage of hydrogen and the attachment of oxygen, especially to unsaturated olefinic fuel molecules. Antioxidants (additives) can prevent or effectively interrupt the process of oxidation and polymerization caused by the formation of "free radicals" during the process.

Oxidation stability is measured in a lab by artificially ageing fuel for sixteen hours in an open vessel aerated by

pure oxygen (3 l/h) at a temperature of 95°C (EN ISO 12205). No more than 25 g/m³ of soluble and insoluble resinous material may form. The quantity of resinous material this method measures in commercially available diesel fuels is substantially lower, generally below 1 g/m³. A new test method has been developed for fuels containing FAME and was introduced in the European standard EN 590 and pr EN 15751. In this test, filtered air is fed through the fuel sample and the air-fuel vapor is passed through distilled water. The water's electrical conductivity is measured. The time measured until a steep rise in conductivity is observed is employed as a quality criterion. A minimum of twenty hours is required. At present, this test method is unsuitable for pure hydrocarbon fuels.

4.1.9 Future Trends

Their high efficiency, which enables fuel economizing, and the still competitive production costs of diesel fuels compared to gasoline will ensure diesel engines retain a large share of the engine market for road vehicles for a long time. Growing acceptance engendered by diesel engines' effective exhaust gas aftertreatment systems as well as good drivability, high performance and reduced noise emissions will encourage this trend and wrest more market share from gasoline engines. Recent successes in racing clearly document this development. Moreover, the consumption of diesel fuel is steadily increasing. Alternative resources for the production of diesel fuel from biomass are well established.

However, vegetable oils are unsuitable for current and future engines without chemical processing. Conversion enables producing products, e.g. vegetable oil methyl ester or fatty acid methyl ester (FAME), that may be used as fuels when they meet the requirements formulated by the working group TC19/WG24 (see Sect. 4.2). These products may be blended into petroleum-based diesel fuel.

A number of countries stipulate small concentrations of FAME as a blending compound to reduce CO₂ emissions. Accordingly, the European standard EN 590 allows blending a maximum of 7% FAME (which in turn must comply with the requirements of EN 14214 [4-6]). The basis for this is the EU Biofuels Directive 2003/30/EG [4-7]. However, the quantities

are small at present because availability is limited, in part because products from certain region are unacceptable since they potentially damage rain forests. In the past, only tax breaks made biodiesel competitive. However, the costs of biodiesel production were recently in ranges similar to conventional diesel fuels because of the significant rise in crude oil prices.

Quality requirements and monitoring are even more important for biodiesel since the quality of natural products varies more greatly. While the use of biomass to produce fuel holds promise in the medium and long-term, its short-term development is unclear. As tax privileges for and compulsory blending of conventional diesel fuel expire, biodiesel as a separate, pure variety may only be expected to retain a small market share, especially since its use in conjunction with state-of-the-art exhaust gas aftertreatment systems is not without problems.

Engines and fuels, especially their synthetic components and additives, are both being developed further. Developments in the production of fuel components from renewable raw materials are also promising. Unlike rape oil methyl ester, these, e.g. CHOREN's BTL process (see Sect. 4.2.2.4), are able to utilize entire plants or residues as raw material. Such developments will also further postpone the longer range depletion of conventional diesel fuel.

4.2 Alternative Fuels

4.2.1 Introduction

Globally increasing energy consumption, related emission of gases that affect the climate, the projected depletion of fossil fuels (see Sect. 4.1.2), unstable political situations in important petroleum and natural gas supplier countries and rising energy prices are intensifying the search for possible alternatives to conventional diesel fuels and gasolines produced from petroleum and for solutions for a secure and sustainable supply of fuel. The goal of sustainability has been outlined in the demand in [4-8] to "Limit transport related greenhouse gas emissions emissions to sustainable levels," i.e. "to eliminate transportation as a major source of greenhouse gas emissions.... This likely will require both the development of hydrogen as a major transport energy carrier and the development of advanced biofuels." However, sustainability also requires an ecological and economic balance that incorporates sociological aspects.

Figure 4-19 presents an overview of potential fuel paths.

Basically, two groups of fuel alternatives have been identified [4-9]:

- conventional fuels based on fossil fuels as well as synthetic fuels and hydrogen and

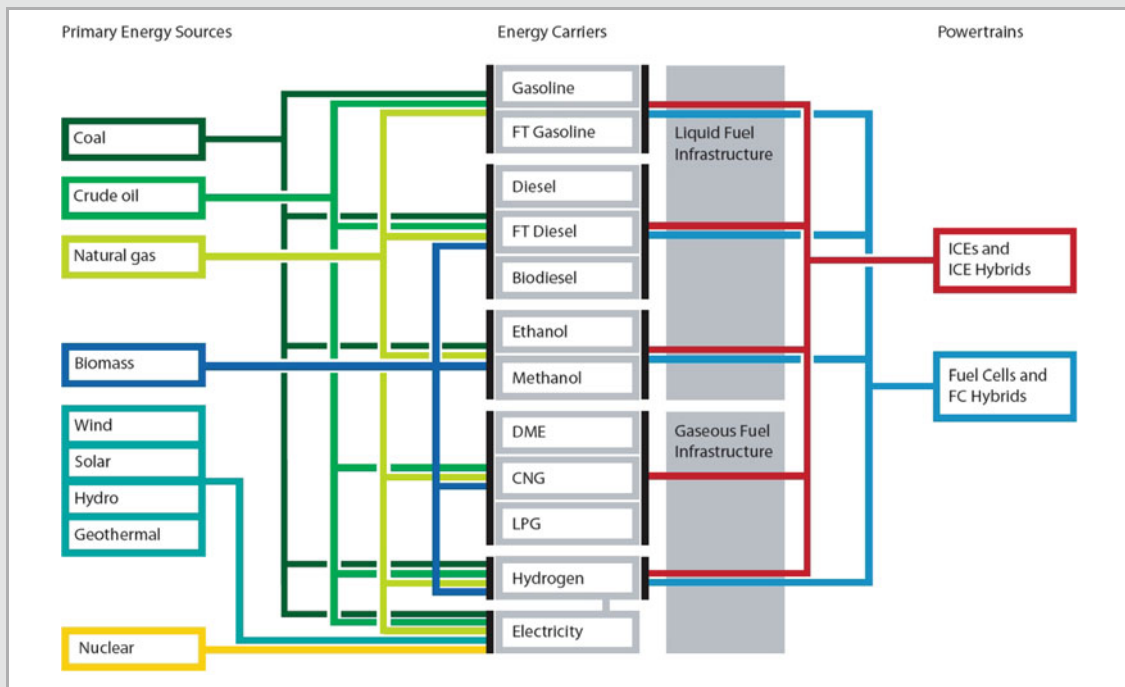


Fig. 4-19 Potential fuel paths (source: WBCSD, Mobility 2030, 2004 [4-8])

- renewable alternatives from, among others, biogenic energy, water power or photovoltaic.

Fuel contributes to meeting the stated goal in two ways:

1. Directly (in/at the engine):
 - improved energy conversion in conventional combustion systems,
 - prevention of the formation of pollutants and
 - new, alternative combustion systems and exhaust gas aftertreatment systems.
2. Indirectly:
 - closed CO₂ cycle for biofuels and
 - reduction of fuel's C/H ratio up through H₂.

Short to medium-term, this yields three groups of alternative fuels:

- synthetic fuels from fossil fuels (GTL),
- first and second generation biofuels and
- low to carbon-free fuels (CNG to pure hydrogen).

Hydrogen powered fuel cells presently have the potential for maximum efficiency as a single energy supply for vehicles. However, this is conditional on the availability of renewable hydrogen since hydrogen can only help reduce CO₂ emissions when it is also produced from primary energy free of CO₂. Three critical technological barriers are hampering this:

- the lack of a storage system for mobile use that is acceptable to customers,
- the lack of a distribution infrastructure and
- the lack of an economically feasible technology to produce renewable hydrogen.

Since a technological solution to these three barriers is not yet available, hydrogen and thus fuel cell drives as well only constitute a long-term solution.

If hydrogen will only be available in the long-term, then a short to medium-term solution that also has real prospects in the long term also becomes a challenge.

The four basic requirements for a future fuel for road vehicles (and in a broader sense also for ships, rail vehicles and aircraft) are:

- high power density,
- certain supply,
- overall economic feasibility and
- the incorporation of environmental and climate protection requirements.

No currently available energy source, not even hydrogen, fulfills these requirements.

A multitude of variants have been discussed and also researched in part [4-10]. A trend toward increased diversification of fuels is emerging. Figure 4-20 presents an overview of the most frequently discussed variants.

Alternative fuels may be classified according to their primary energy, type of production and properties, thus making it possible to define groups of liquid fuels made from vegetable oils and fats, alcohol fuels produced by fermentation and gaseous fuels. Alternative liquid fuels obtained from agricultural products are called first generation biofuels. Their use is controversial because their production competes with food production. Liquid synthetic fuels with properties that can be influenced by the production process are becoming increasingly important. Synthetic fuels made from renewable biomass (utilizing the entire plant) are second generation biofuels.

4.2.2 Liquid Fuels

4.2.2.1 Fuels from Vegetable Oils and Fats

Vegetable oils are pressed from oleaginous fruits. Rudolf Diesel already recognized their utilizability in diesel engines. Their high energy content approaching diesel fuel's is

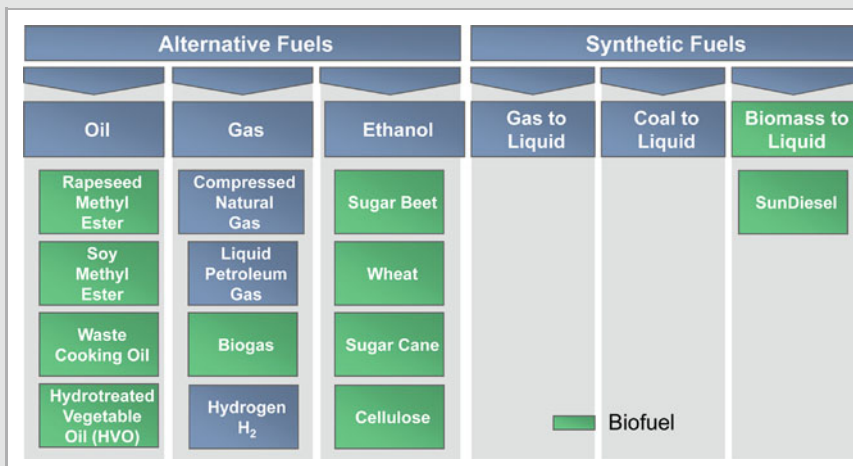


Fig. 4-20
Overview of alternative fuels

advantageous. However, their inadequate physical properties such as viscosity and high boiling temperature that result in poor combustion are highly disadvantageous.

In addition, their cold start performance is unsatisfactory and they are only stable in storage for a limited time. Some characteristic values of vegetable oils are compared with diesel fuel in Table 4-7.

Pure Vegetable Oils

The fuel properties of vegetable oils necessitate modified engines. Rape oil has acquired limited importance for powering agricultural machinery and tractors [4-11]. Compliance with the fuel standard is important [4-12].

The automotive industry rejects the use of pure vegetable oils as well as their blending in diesel fuel because of their poor fuel properties. Another potential use of vegetable oils for fuel production might be their addition to the refinery process, the outcome being a higher quality diesel fuel partially produced from biomass [4-13].

Biodiesel

The term biodiesel (also called first generation BTL) originally denoted esterified rape oil (rape oil methyl ester or RME): Esterifying this vegetable oil fundamentally improved its

properties. The term biodiesel has been expanded to include esterified fatty acids (vegetable oils, animal fats and used cooking oils).

A blend of up to 7% biodiesel (B7) by volume in diesel fuel is now accepted in accordance with EN 590 and DIN 51628. This corresponds to the European standard EN 14214 for fatty acid methyl ester (FAME) [4-1, 4-6]. Once larger areas of the market are supplied with a 7% blend (e.g. EU 25), the biodiesel content could conceivably be increased by up to 10% by volume (B10) at first and even by up to 20% by volume (B20) later, provided the appropriate compatibility tests have concluded successfully. Problems may well arise, specifically with the latest diesel engine engineering and particulate filter systems. Should acceptance nevertheless still be possible, EN 590 shall have to be revised in due time.

Pure biodiesel (B100) is unlikely to receive any further approval for car engines in the future for reasons of emissions.

4.2.2.2 Alcohols

While alcohols possess excellent combustion properties, their energy density (vehicle range), cold start performance and corrosion behavior toward metals and elastomers are significant disadvantages (Table 4-8). Hence, larger percentages of alcohol (>15% by volume) necessitate the development of special engines.

Table 4-7 Comparison of vegetable oil and diesel fuel specifications (DF)

Parameter	Unit	Diesel	Rape Oil	Sunflower Oil	Linseed Oil	Soy Oil	Olive Oil	Palm Oil
Density	g/cm ³	0.83	0.915	0.925	0.933	0.93	0.92	0.92
Viscosity (20°C)	mm ² /s	≈2	74	65.8	51	63.5	83.8	39.6
Calorific value	MJ/kg	43	35.2	36.2	37.0	39.4	(40.0)	35
Cetane number	—	50	40	35.5	52.5	38.5	39	42
Flash point	°C	55	317	316	320	330	325	267

Table 4-8 Fuel specifications of alcohols

Characteristic value	Unit	Gasoline	Diesel	Methanol	Ethanol
Calorific value	MJ/kg	≈42	42–43	19.7	26.8
Calorific value	MJ/dm ³	≈32	36	15.5	21.2
Stoichiometric air requirement	kg/kg	14–14.7	14.5	6.46	9.0
Calorific value of the air/fuel mixture	kJ/kg	≈2,740	2,750	2,660	2,680
Density	kg/m ³	730–780	810–855	795	789
Boiling temperatures	°C	30–190	170–360	65	78
Heat of evaporation	kJ/kg	419	544–785	1,119	904
Vapor pressure	bar	0.45–0.90	—	0.37	0.21
Ignition limits at λ _v		0.4–1.4	0.48–1.40	0.34–2.00	—
Cetane number		—	45–55	—	—
Octane number ROZ		98–92		114.4	114.4
MOZ		88–82		94.6	94.0
Sensitivity MOZ – ROZ		≈10	—	≈20	≈17

Methanol

Methanol is primarily produced from primary fossil fuels (natural gas, coal). However, renewable energy sources (biomass) may also be used. Methanol in the form of methyl tertiary butyl ether (MTBE) is primarily added to gasoline as an anti-detonation agent. EN 228 allows up to 15% MTBE. Up to 3% methanol may also be directly added secondarily. Larger percentages of methanol ought to be avoided for reasons of toxicity.

Ethanol

Ethanol is fermented directly from sacchariferous or amylaceous raw materials (grains, sugar beets, sugar cane, etc). Wood and culmiferous feedstocks may be used when the lignocellulose (e.g. straw) is pulped enzymatically. Such a process was developed by the Canadian company IOGEN [4-14] and has been implemented on an industrial scale (Fig. 4-21).

Ethanol is suitable for gasoline engines. First and foremost, EN 228 calls for up to 15% ethyl tertiary butyl ether (ETBE) by volume (47% ethanol content) [4-15]. Secondly, EN 228 allows directly using up to 5% ethanol (E5) by volume [4-16]. It is impossible to supply all of Europe at present because too little is available. Should the rapidly growing capacities make this possible in the future, it may initially increase to 10% by volume (E10) and later even up to 15% by volume (E15). Many new gasoline engines entering the market are already designed for a 10% blend. However, EN 228 shall have to be duly revised.

E85 and FFV (flexible fuel vehicles) will only be justified once large quantities of ethanol become available on the entire fuel market (e.g. in Brazil).

Blending ethanol with diesel fuel for cars is largely rejected because of the poor mixture stability and other problems, yet is locally important for commercial vehicles deployed in fleets (e.g. in the USA and Brazil) [4-17].

4.2.3 Gaseous Fuels

Gaseous under ambient conditions, these fuels (see Sect. 4.4) have extremely low energy density (relative to volume) and require considerable technology, in part to be stored on board a vehicle.

4.2.3.1 Natural Gas

Natural gas (predominantly methane) is a natural fossil fuel, the processing of which merely entails cleaning and the removal of sulfur and other disturbing components. In the future, it will be used increasingly in nonroad domains (power plants and CHP). Biogas processed into fuel gas with the quality of natural gas is a sustainable alternative with a potential that cannot be ignored [4-18].

Storing natural gas on board a car to guarantee acceptable ranges is very complex:

- Either it is stored liquefied at -167°C (liquefied natural gas or LNG). This is connected with high evaporation losses when a vehicle is stopped for longer periods and thus has not established itself for use in cars.
- Or it is stored gaseous at approximately 200–250 bar (compressed natural gas or CNG) in large, weight-optimized pressure tanks.

Natural gas has high detonation limits and is therefore particularly suited for gasoline engines.

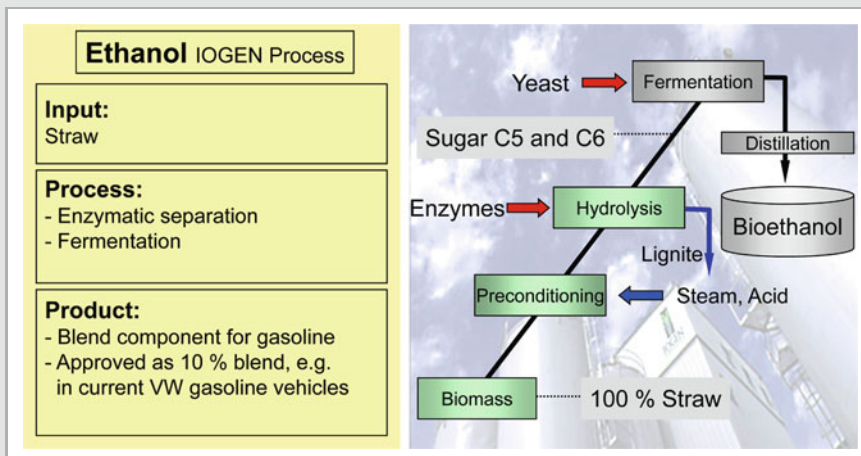


Fig. 4-21
The IOGEN process for bioethanol production (2nd generation)

In Germany for instance, substantial tax cuts have ensured that natural gas will enjoy increasing use in the coming years. Natural gas can be and is used to power vehicles directly. However, in light of the known disadvantages of all gaseous fuels in terms of range, the space requirements for tanks and the increased work exhaust gas aftertreatment requires to comply with strict emission limits, natural gas may only be expected to supplement fuels to a limited degree, not replace them.

Natural gas has achieved a certain level of importance in road traffic in some markets such as Italy, Argentina and Russia (and is used in approximately four million vehicles worldwide) and is anticipated to have a market share of approximately 5% in Europe by 2020.

4.2.3.2 Liquefied Gas

A butane-propane mixture, liquefied gas or liquefied petroleum gas (LPG) is a companion product of petroleum production and processing and thus of fossil origin. Its limited sales volume has only enabled it to garner a niche market. It may be stored on board vehicles as a liquid at a pressure of approximately 5–10 bar. LPG is used practically only in conjunction with spark ignition.

Liquefied gas has achieved particular importance in road traffic especially in Italy, the Netherlands and Eastern Europe (and is used in approximately nine million vehicles worldwide). LPG vehicle lines are basically only retrofits.

4.2.3.3 Dimethyl Ether (DME)

DME can be produced from natural gas or biomass. Like LPG, it may be stored as a liquid on board a vehicle at a pressure of approximately 5–10 bar.

DME is a suitable fuel for diesel engines. Its excellent combustion properties (soot-free and low NO_x emissions) are undercut by the disadvantages of its low lubricity, low viscosity, low energy content (halving of the range) and corrosiveness.

An injection system would have to be appropriately refined since the fuel in the tank is under pressure. The high costs and low quantities render this idea unsustainable.

4.2.3.4 Hydrogen

Clearly, renewable hydrogen can help relieve the environment. Nevertheless, a well-to-wheel analysis demonstrates that the use of fossil hydrogen in the transportation sector does not make any sense because of the CO₂ emissions.

Storing hydrogen on board a car to guarantee acceptable ranges is very complex:

- It is stored liquefied at -253°C . This is connected with high evaporation losses when a vehicle is stopped for longer periods.
- Or it is stored gaseous at approximately 700 bar.
- Or it is stored in large, heavy metal hydride tanks.

A tank shape that is cost effective from the perspective of mass production is not in sight. The absence of cost effective renewable hydrogen production and the extremely capital-intensive infrastructure required to produce and market it make it improbable that both hydrogen and fuel cell technology will become marketable and competitive enough for mass production within the next two decades.

4.2.4 Synthetic Fuels

Parallel offerings of every fuel on the market, e.g. diesel, gasoline, methanol, ethanol, natural gas and other fuels, cannot be a cost effective solution since every one of these fuels not only necessitates the development of an independent engine but also an independent distribution infrastructure. Hence, blending alternative fuels into standard fuels within acceptable upper limits makes considerable sense. The sale and use of these blends are assured everywhere.

The introduction of other alternative energies on the market will require seeking an opportunity to diversify the primary energies and simultaneously restrict the energy sources being utilized for vehicles to a minimum of variants. Synthetic fuels such as gas-to-liquid (GTL) and biomass-to-liquid (BTL) provide such an opportunity.

4.2.4.1 Fossil Fuels (GTL)

Well known and industrially tested processes such as Shell Middle Distillate Synthesis (SMDS) can be used to produce other secondary energy carriers from natural gas.

At present crude oil price levels, such gas-to-liquid technologies are highly economical in many regions of the world with supplies of inexpensive natural gas or oil-associated gas. Companies such as Shell, Sasol, ConocoPhillips and Chevron have begun expanding their production capacities considerably. Nonetheless, given the investments and construction of synthesis plants this requires, five to eight years will certainly pass before the supply of these synthetic fuels is stable. Thus, this only constitutes a short to medium range solution.

Synthetic fuels hold great potential to improve the engine combustion process. The specification of a synthetic diesel fuel is impressive, most notably because of its high cetane number and absence of aromatics and sulfur.

The improvements of emissions with the synthetic fuel Shell GTL over a commercially available sulfur-free diesel fuel are presented in Fig. 4-22 as an example.

The latest technology has proven to provide a basis for substantial improvements as well – Golf TDI vehicles met Euro 4 limits even with diesel fuel. Without modified calibration or other measures, a reduction of particulate emissions of over 50% was measured in part even in older concepts that only comply with Euro 3 exhaust legislation. Thus, even these vehicles were below the Euro 4 limits of particulate matter [4-19].

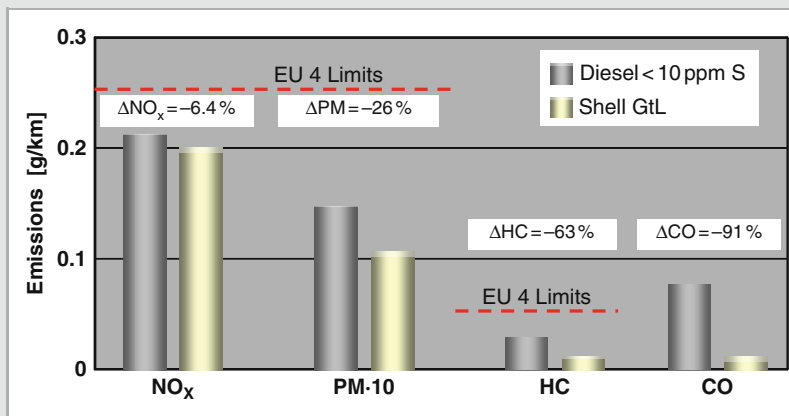
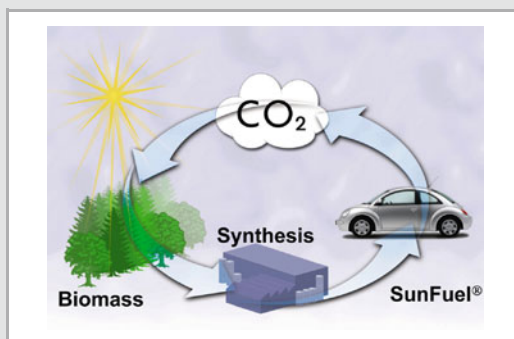


Fig. 4-22

Comparison of synthetic fuel (GTL) and diesel fuel emissions (fleet test with 25 VW Golf 1.9 TDI in Berlin in 2003)

4.2.4.2 Renewable Sources (BTL)

Once the input stages have been modified accordingly, the production process for synthetic fuels will be able to use the widest variety of primary energy sources, e.g. even renewable energy sources such as residual timber, residual straw, energy plants or biowaste. Even wastes largely ignored before will become highly interesting residual materials that may be supplied as more material and subsequently as energy. A crucial advantage is the independence of the final product's quality from the nature of the primary energy used. The energy stored in the world's annual crop growth corresponds to approximately fifty times humankind's energy consumption, i.e. tremendous potential for substitution exists. From a policy perspective as well, the use of biomass relieves the supply sector since, unlike fossil energy sources, biomass is distributed relatively uniformly all over the world. While, this does not reduce local CO₂ emissions to zero, it does create a nearly neutral CO₂ cycle for which the sun delivers the operating power (see Fig. 4-23). Thus, the fuel cycle is integrated in the natural CO₂ cycle into which approximately 98% of all CO₂ emissions are routed.

Fig. 4-23 CO₂ cycle with BTL (SunFuel®)

The biomass available is basically dispersed among residual materials and cultivated energy plants. Widely varying views exist about the potential to substitute existing fuels. Literature that postulates a potential of 10% to 15% in Europe takes the actual present situation as its point of departure. Agriculture will be able to massively increase yields as soon as the target of breeding and production is optimized quantity rather than quality food plants. Bearing these factors in mind, a potential for approximately 25% substitution could presumably be reached by 2030 [4-20].

Along with analyses of the cultivation of different fast growing timbers and special energy plants (see Fig. 4-24), residual materials and, in particular, the potential of industrial and municipal biowastes and other wastes deserve in depth study. In the future, all collections of biomass could be fed to the production of high grade fuels instead of composting.

Figure 4-25 schematically depicts a plant that produces SunFuels® based on the BTL process. Depending on the process, pyrolysis converts the biomass into gaseous, liquid and solid constituents in an initial stage. The CHOREN pyrolysis process [4-21] produces a pyrolysis gas and biocoke. Other processes of Canadian and American companies chiefly produce solid or liquid substances as the pyrolysis product, which are called biocrude. This pumpable primary product is similar to crude oil. When it is precompressed in smaller distributed units, biomass is particularly suited for transport to a large central plant. This can increase the efficiency of the actual central production plant considerably, without the biomass transport negating the efficiency of the entire product chain. Such pyrolysis plants remain within a financially manageable scope and may even be operated by communities or agricultural machinery cooperatives in place of composting plants. Another advantage is the usability of both moist and dry feedstocks as well as the potential to remove the mineral constituents and return them to the soil as fertilizer.

A second stage, the actual gasification, produces a synthesis gas. After appropriate cleaning, Fischer-Tropsch synthesis

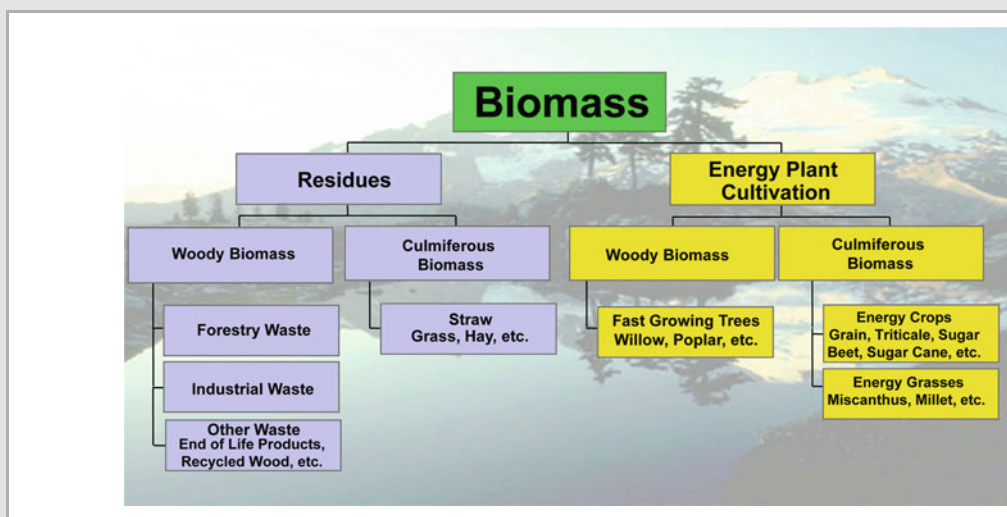


Fig. 4-24 Energy plants utilizable to produce SunFuel[®]

(FT synthesis) followed by hydrogenation and subsequent distillation converts the synthesis gas into high grade fuel and waxes. The waxes serve as a basis for the production of synthetic oils that are predominantly produced from petroleum and natural gas at present.

Since it is not yet economically feasible, this biomass-to-fuel solution (also called second generation BTL) also remains a medium range prospect. The pure production costs without taxes (based on a production plant sized for 200 MW_{th}) tally up to a cost disadvantage of approximately 20–30 cents per liter compared with fuel from fossil sources (with production costs of approximately 35 cents per liter at a crude oil price of \$50 per barrel). However, the production costs are significantly lower than current service station prices. Thus, until its

economic feasibility can be demonstrated, it lies in government's hand to promote the development of the process through appropriate tax laws and the initial introduction of the fuel. In and of itself, Germany's tax exemption of BTL fuels until 2015 will not be enough to ensure this.

The nearly unlimited possibilities to sell this fuel additionally furnish a tremendous opportunity to safeguard jobs in agriculture. Particularly in light of the restructuring of EU subsidy guidelines, the provision of energy plants could also stabilize income in the long-term. The development and construction of production plants will furnish industry a new source of revenue too.

As soon as it is available, less expensive renewable hydrogen could also be added to the SunFuel[®] production process.

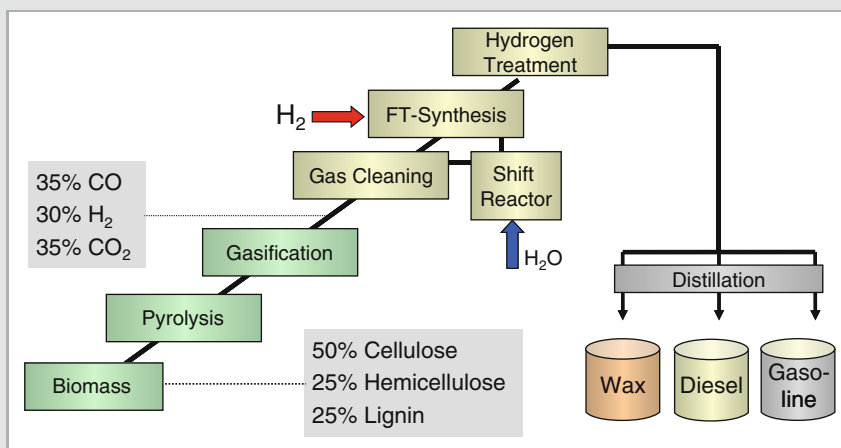


Fig. 4-25
Flow chart of BTL production [4-21]

This would allow nearly doubling the yield of fuel. It also means that the establishment of a hydrogen industry would not inevitably result in the utilization of hydrogen in the mobile economy. Viewed holistically, biomass-based synthetic fuels could prove to be expedient, especially in terms of sustainability.

Alternative energy sources will rapidly become more important in the future as the technical limits of petroleum production are approached and the world's demand for energy increases. The demands on conventional fuel's quality and purity are rising too. Related cost increases are encouraging the introduction of generally more expensive alternatives. Volkswagen AG anticipates an evolution of fuel in the coming years, which will proceed from conventional petroleum-based fuels to synthetic SynFuels produced from natural gas up through biomass-based SunFuel[®]. Hydrogen will only be able to play a role as an energy source in mobile applications in the distant future once every technological barrier has been eliminated. Figure 4-26 describes such a scenario.

The intermediate stage between first and second generation biofuels has been dubbed NExBTL [4-13]. This is a BTL fuel obtained from vegetable oils and animal fats by means of FT synthesis and, like GTL, usable as a blend component in conventional diesel. Table 4-9 compares the most important properties.

Given the constraints on present day knowledge about the utilization of agricultural lands and the efficiency of the processes, substituting 15 to 20% of the EU's fuel requirement with SunFuels[®] appears possible. Higher values also appear realizable by improving biomass production, processes and logistics. However, stable boundary conditions such as a sustainable commitment to biofuels on the part of government are also a prerequisite.

The EU's biofuel directive to promote the use of biofuels or other renewable fuels in the transportation sector [4-7] defines biofuel fractions as reference values based on an energy content of 2% in 2005 and 5.75% in 2010.

The EU intends to revise its biofuel directive by 2008. Among other things, issues of cost effectiveness and the environmental impact of biofuels shall be incorporated and objectives shall be formulated for the period after 2010. Improving the boundary conditions for higher blending ratios in conventional fuels will also be essential.

4.2.5 Life Cycle Assessment

An analysis of all the phases of the life cycle is particularly important for the development of future environmentally friendly propulsion and fuel concepts. Merely optimizing just one segment of the life, e.g. a car's use phase and its attendant emissions, does not always deliver the ecological optimum when the entire life cycle is analyzed.

Therefore, life cycle assessment is used as an instrument to analyze a product's environmental profile throughout its entire life cycle. Life cycle assessments identify the time and way one ecological problem is solved at the cost of another. Shifting problems become recognizable and environmental strategies can thus be formulated more reliably.

In a joint project, DaimlerChrysler and Volkswagen developed a comparative life cycle assessment of SunDiesel and conventional diesel to evaluate the environmental profile of BTL fuels throughout their entire life cycle. The cultivation of biomass, the synthesis of fuel from biomass and the use of the fuels in vehicles were analyzed. The BTL fuel analyzed had been produced from wood with the CHOREN process (Fig. 4-27).

The study came to the conclusion that SunDiesel can cut between 61 and 91% more greenhouse gases than conventional

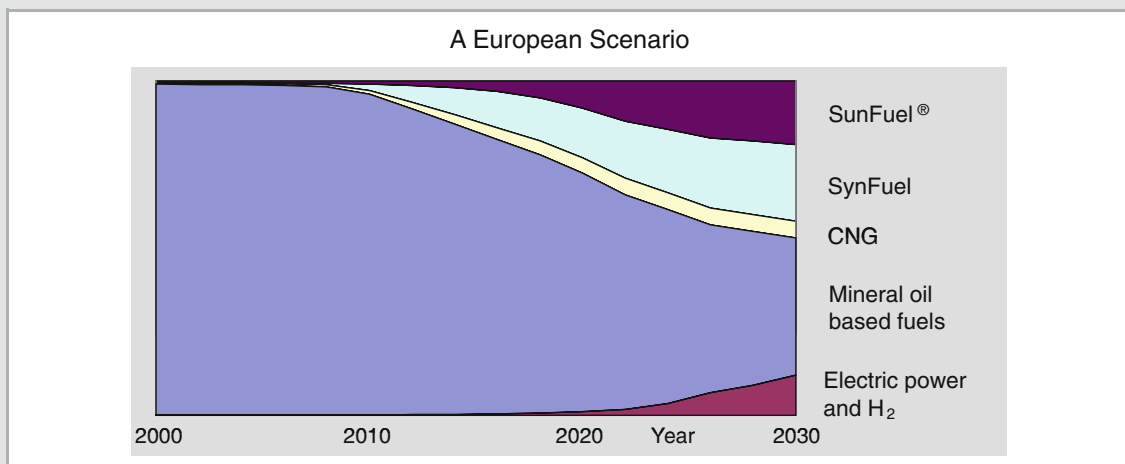


Fig. 4-26 European scenario for energy carriers in mobility

Table 4-9 Properties of alternative fuels [4-13]

	NExBTL	GTL	FAME (RME)	Swedish class 1 diesel	Summer DF (EN 590)
Density at +15°C (kg/m ³)	775 ... 785	770 ... 785	≈885	≈815	≈835
Viscosity at +40°C (mm ² /s)	2.9 ... 3.5	3.2 ... 4.5	≈4.5	≈1.8	≈3.5
Cetane number	≈80 ... 99	≈73 ... 81	≈51	≈53	≈53
Distillation 90% by volume (°C)	295 ... 300	325 ... 330	≈355	≈280	≈350
Cloud point (°C)	≈-5 ... -25	≈0 ... -25	≈-5	≈-30	≈-5
Calorific value (MJ/kg)	≈44.0	≈43	≈37.5	≈43	≈42.7
Calorific value (MJ/l)	≈34.4	≈34	≈33.2	≈35	≈35.7
Total aromatics (percent by weight)	0	0	0	≈4	≈30
Polyaromatics (percent by weight)	0	0	0	0	≈4
Oxygen content (percent by weight)	0	0	≈11	0	0
Sulfur content (mg/kg)	<10	<10	<10	<10	<10
Lubricity HFRR at +60°C (μm)	<460	<460	<460	<460	<460

diesel throughout the entire life cycle. These cuts are primarily based on the CO₂ emissions from normal driving being reabsorbed by growing plants and CO₂ consequently being routed into the cycle.

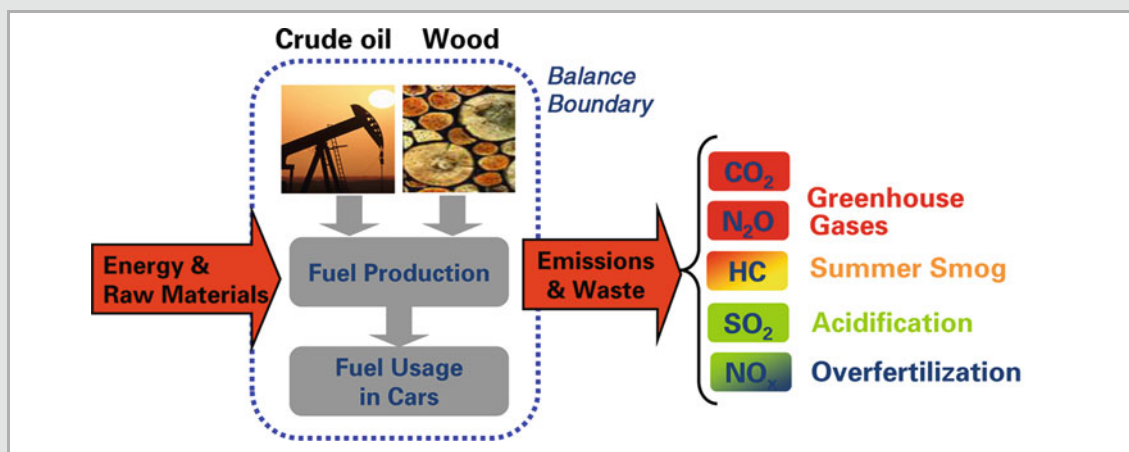
In addition, the use of SunDiesel also lowered the hydrocarbon emissions that contribute to summer smog approximately 90% over conventional diesel. The lower HC emissions during normal driving and the HC emissions prevented during drilling and refining crude oil for conventional diesels are responsible for this.

An analysis of the entire life cycle leads to holistic ecological product development. Precise analyses replace blanket assumptions. Thinking in life cycles identifies the concrete boundary conditions under which certain propulsion or fuel strategies may be formulated more environmentally compatibly.

The diesel fuel produced from wood with the BTL process is nearly CO₂-neutral and, based on the analysis, deserves to be called SunFuel[®] for good reason.

4.2.6 New Combustion Systems

All these considerations demonstrate that liquid hydrocarbons will presumably be available and dominant as fuel even in the coming 30 years. At the same time, synthetic fuels furnish potential to optimally adapt fuel properties to combustion. Further reducing exhaust emissions or reducing the considerable complexity of exhaust gas aftertreatment will only be feasible when, first and foremost, the raw NO_x emissions of stratified combustion systems can be lowered. This means the production of NO_x must be suppressed during combustion without diminishing engine efficiency, making it essential to retain direct injection quality control. This will

**Fig. 4-27** Results of the SunDiesel life cycle assessment

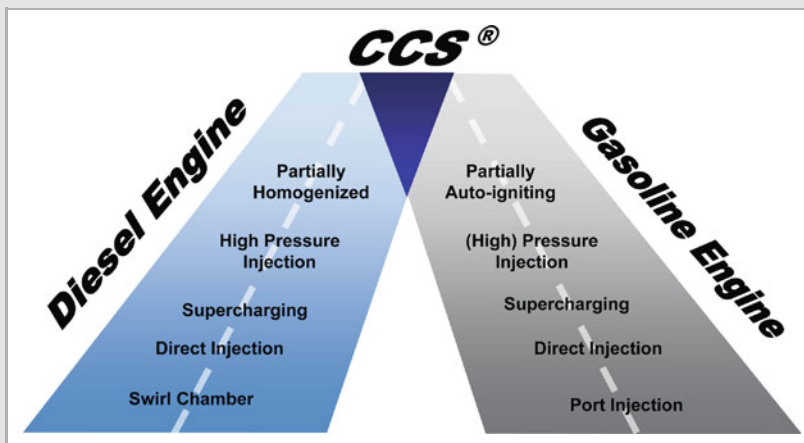


Fig. 4-28
Evolution of engine combustion systems

necessitate uniting the respective advantages of gasoline and diesel engines in one new process (see Sect. 3.3).

The combustion systems of both engine concepts had already grown significantly more alike when direct injection was introduced for gasoline engines too. The next stages in combustion system development will entail intensifying this trend (see Fig. 4-28).

The development of “partially homogenized diesel combustion” and the current stage of development of “auto-igniting gasoline engines” in research and development labs are likewise already based on hardware with a comparable core. Thus, developing a new combined combustion system that subsumes the fundamental features of both systems is only logical. Volkswagen calls this a combined combustion system (CCS). The basis of the system is a new synthetic fuel with modified specific properties [4-22, 4-23].

Numerous obstacles still have to be overcome to implement the CCS. Hence, a market launch may no longer be expected in this decade.

4.2.7 Conclusion

Figure 4-29 presents a complete potential scenario for the development of future drives and related fuels [4-24].

Present day petroleum-based fuels and conventional engines will facilitate further decreases of specific CO₂ emissions that correspond with the automotive industry’s voluntary commitments and technical advances. Engines with direct fuel injection will play a key role.

In addition to petroleum-based fuels, synthetic conventional fuels primarily based on natural gas will be launched on the market this decade. Since all the commercial features and distribution structures shall be retained, the introduction of synthetic fuels will not change anything for vehicle users. Synthetic fuels are free of sulfur and aromatics and their properties can be tolerated more narrowly than current fuels. These advantageous properties will enable carmakers

to further develop their products to reduce fuel consumption and improve emissions, especially in diesel engines.

If, instead of being produced from fossil fuels, synthesis gas is produced on the basis of CO₂-free or CO₂-neutral energy, then the specific CO₂ emissions of vehicle operation will drop even when consumption remains unchanged. This holds true regardless of the type of fuel, i.e. even synthetic fuel made of renewable raw materials (SunFuel®). The great advantage of this route is its retention of the current fuel infrastructure even in this phase.

In the medium term, novel engine combustion systems will be implemented, which will combine the consumption advantages of present day diesel engines with the emission potential of gasoline engines and their exhaust gas aftertreatment. The appropriate fuels will have to be customized for these hybrid combustion systems. Synthetic fuels (SynFuel and later SunFuel®) provide the best conditions for this.

Above all, the electric motor is regarded as the optimal drive for sustainable mobility in the long term. Whether such vehicles will have advanced battery systems or hydrogen as the energy source with fuel cells as energy conversion systems is still hard to judge. This is unlikely in the next 20 years at the least. Whatever system establishes itself later, one undisputed advantage will be its ability to generate electrical power and hydrogen from renewable energies such as wind, water or sunlight. The fact that electric motors do not cause the local emissions combustion engines do is advantageous too.

4.3 Operation of Marine and Stationary Engines with Heavy Fuel Oil

4.3.1 Heavy Fuel Oil

Heavy fuel oil is a mixture of residual oils that accumulate from fractionated distillation during petroleum (crude oil) processing. Their main constituents are hydrocarbon

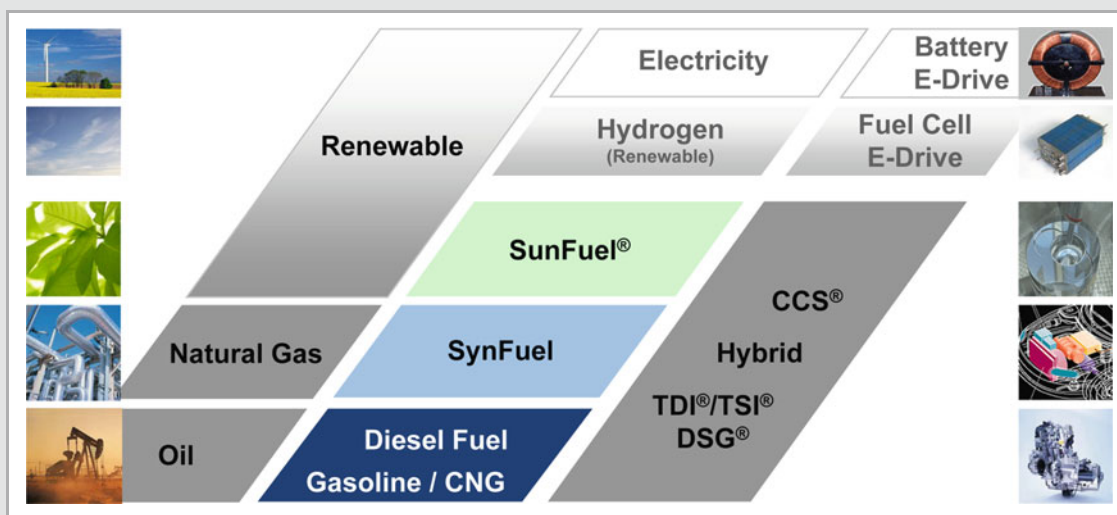


Fig. 4-29 Volkswagen's fuel and power train strategy

compounds that remain as high boiling fractions after crude oil has been distilled. Since residual oils are considerably less expensive than distillates, e.g. gasoline or light fuel oil, there is an economic incentive to use these components as fuel.

In most cases, distillates are blended into the residual oils to secure specific product properties and, in particular, to adhere to a predefined upper viscosity limit.

Heavy fuel oils have viscosities between 4.5 and 55 mm²/s (cSt) relative to 100°C and are specified in the standard ISO 8217.

On the basis of this ISO standard, the Conseil International des Machines a Combustion (CIMAC) classified heavy fuel oils based on their physical-chemical data with even more requirements. These "requirements for residual fuels for diesel engines" are part of the operating specifications issued by every manufacturer of diesel engines compatible with heavy fuel oil (see Fig. 4-30).

The properties or composition of heavy fuel oils vary within broad limits based on the crude oils' provenience and dependent on the different processing processes in the refineries (see also [4-25]). Apart from their significantly higher viscosities, heavy fuel oils are characterized by higher densities, higher sulfur contents and greater propensity to coking than distillates. The incombustible content (ash) is two orders of magnitude higher, the ignition and burning properties are poorer because of the higher aromatic and asphalt contents and appreciable quantities of water and solid contaminants that induce wear may also be present.

Heavy fuel oil's greater density than gas oil's (corresponding to DF) indicates a gain of the weight ratio of carbon to

hydrogen. Regardless of the sulfur content, this reduces the net calorific value H_u (see Fig. 4-31).

The constant tendency of heavy fuel oils to diminish in quality is the result of the increasing spread of such conversion processes as catalytic and thermal cracking in modern refineries to better utilize crude oil. (The residue fraction is 32–57% in classic atmospheric distillation, 12–25% in a conversion refinery.) The high aromatic content connected with this lessens ignition quality (see Sect. 4.3.4.1), the increased asphaltene fraction the stability. Intensified sludge and resin formation can disrupt fuel processing.

Other adverse effects stem from an intensified trend toward disposing of used lubricating oils, organic solvents or chemical wastes in the residual oils.

Adapting diesel engines to the given conditions, assuring the quality of heavy fuel oils through standards (ISO, CIMAC, Fig. 4-30) and, in particular, optimally processing heavy fuel oil are instrumental in making cost effective, trouble-free use of heavy fuel oil possible in diesel engines under these conditions.

4.3.2 Heavy Fuel Oil Processing

Heavy fuel oil must be processed to be used as fuel in diesel engines. This eliminates or largely reduces undesired impurities such as water with any corrosive substances possibly dissolved in it as well as solid impurities such as coke, sand, rust, catalyst residues from the refinery and sludge-like constituents such as agglomerated asphaltenes.



Requirements (1990) for residual fuels for diesel engines (as delivered)

Designation:		CIMAC												
Related to ISO 8217 (87):		F --												
Characteristic	Dim.	Limit												
Density at 15 °C	kg/m ³	max	950											
Kinematic viscosity at 100 °C ¹⁾	cSt ²⁾	max		10										
	min ⁴⁾		6											
Flash point	°C	min		60										
Four point	°C	max		0 ³⁾ 6	24									
Carbon Residue	% (m/m)	max	12	14										
Ash	% (m/m)	max		0.10										
Total sediment after ageing	% (m/m)	max		0.10										
Water	% (V/V)	max		0.50										
Sulphur	% (m/m)	max		3.5										
Vanadium	mg/kg	max	150	300										
Aluminium + Silicon	mg/kg	max		80										
Ignition properties			see appendix, section 3											

¹⁾ Approximate equivalent viscosities (for information only):

Kinematic viscosity (cSt) at 100 °C 6 10 15 25 35 45 55

Kinematic viscosity (cSt) at 50 °C 22 40 80 180 380 500 700

Sec. Redwood I at 100 °F 165 300 600 1500 3500 5000 7000

²⁾ 1cSt = 1 mm²/sec

³⁾ Applies to region and season in which fuel is to be stored and used.
(upper value winter quality, bottom value summer quality)

⁴⁾ Recommended value only. May be lower if density is also lower.

See appendix, part 3

Fig. 4-30 Classification of heavy fuel oils according to CIMAC/ISO (except from the original)

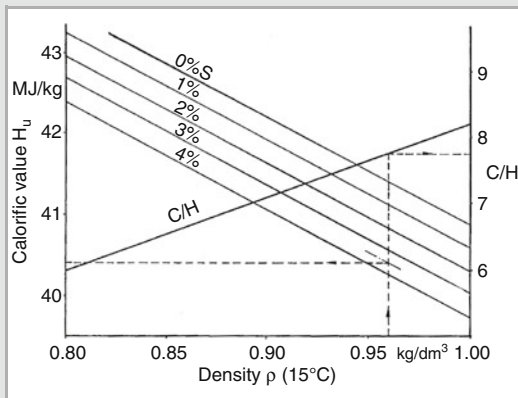


Fig. 4-31 Influence of the carbon/hydrogen ratio C/H on the density ρ and calorific value H_u of heavy fuel oils as a function of the sulfur content

If these damaging impurities are not removed, corrosion and/or wear damage must be expected in the injection system (e.g. pumps and nozzles) and in the engine itself (e.g. on cylinder liners, pistons and piston rings) in the short-term with every aggravating consequence this entails.

Another function of processing is to provide the injection viscosity the heavy fuel oil needs for optimal engine operation. This requires preheating temperatures between 90

and 160 (170)°C, depending on the initial viscosity (see Fig. 4-32).

Figure 4-33 presents the components used in an optimal heavy fuel oil processing system based on the current state-of-the-art.

The heavy fuel oil travels from the storage tanks to the settling tanks. A twenty-four hour residence time at temperatures around 70°C facilitates precleaning.

The next station is the centrifugal separators, which play a key role in the processing system. Connected in a series or in parallel, they act – depending on the setting – as a separating stage (also called a purificator) to remove water and foreign substances or as a clarifying stage (clarificator) to remove only foreign substances. To this end, the heavy fuel oil is preheated to approximately 95°C to obtain low viscosities and high density differences for high purification efficiency.

Modern separators independently adjust to changed heavy fuel oil parameters, e.g. density, viscosity and water content, and are self-emptying as well.

Designed as a buffer for at least eight hours of full load operation, the day tank supplies the heavy fuel oil to the booster system where, controlled by a viscosity controller, it is preheated to the requisite injection viscosity. The system pressure is higher than the evaporation pressure of water to prevent the formation of steam and gas.

An automatic backflush filter with a very fine mesh width (10 µm) provides for the final purification of the fuel and,

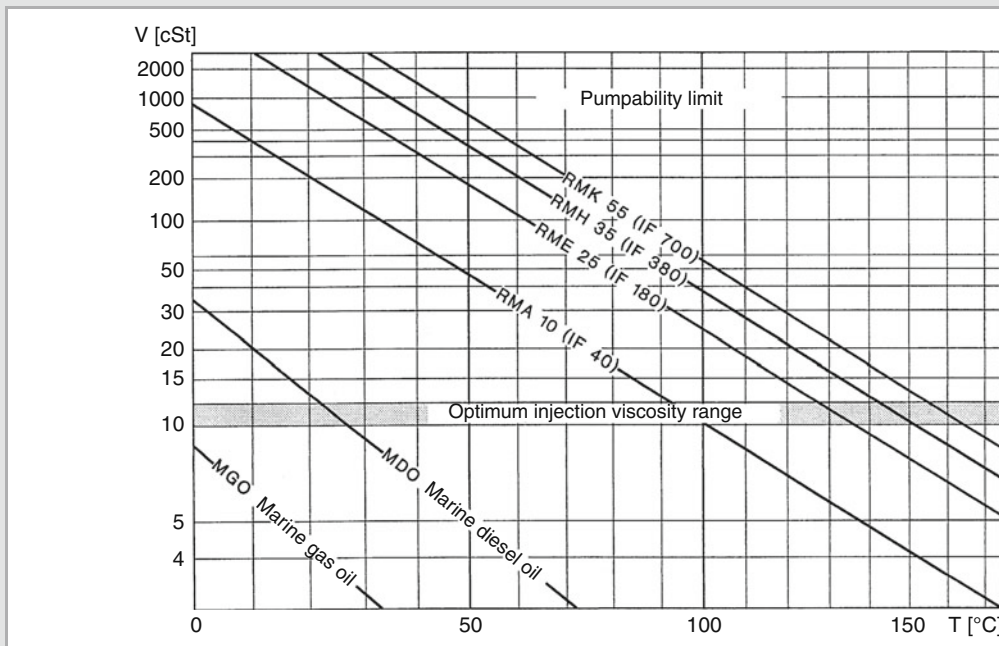


Fig. 4-32 Marine fuels' viscosity/temperature correlation. RMA: Residual marine fuel, class A, based on Fig. 4-30

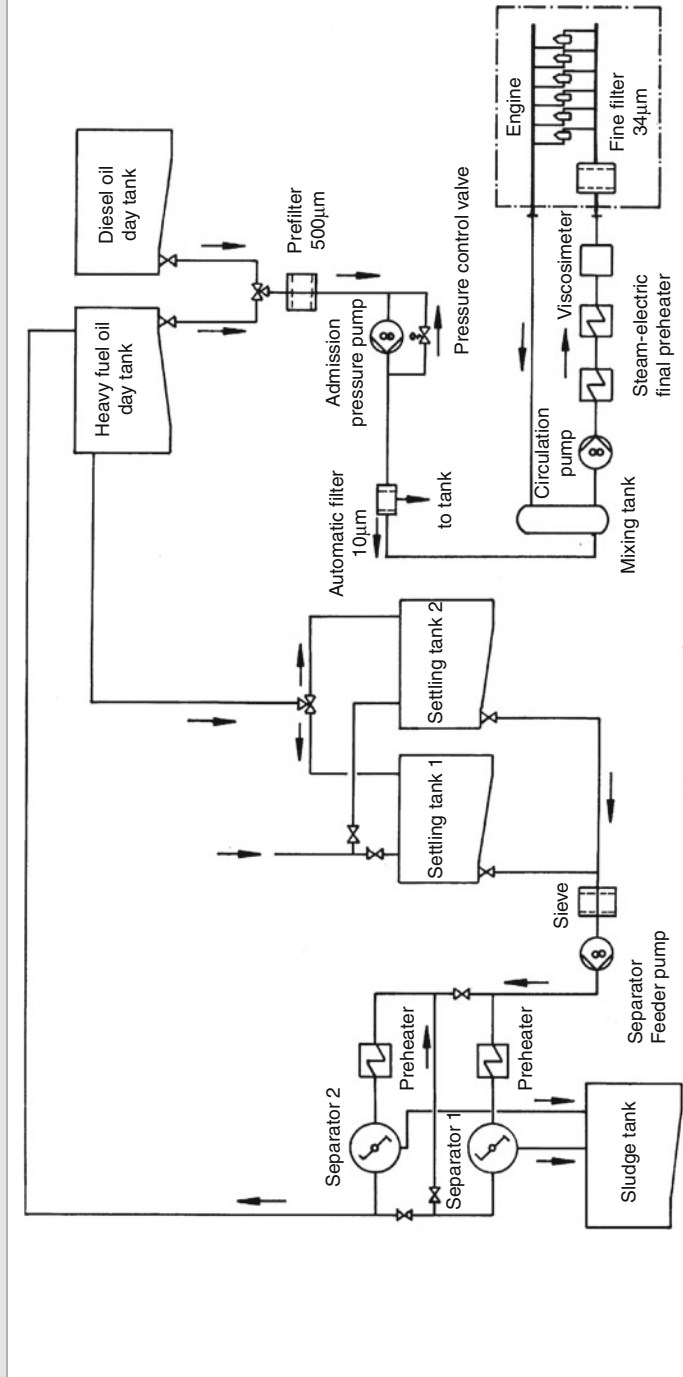


Fig. 4-33 Schematic of a heavy fuel oil processing system

based on its backflushing frequency, constitutes a useful indicator of the effectiveness of the upstream processing elements.

4.3.3 Distinctive Features of Heavy Fuel Engines

4.3.3.1 Heavy Fuel Engines and Their Problems

Heavy fuel oil processing requires both considerable investment and appropriate space for installation. Hence, heavy fuel oil operation is chiefly encountered on board ships and in large stationary engines. Only long operating periods with correspondingly high fuel consumption in conjunction with the price of heavy fuel oil, which is roughly 35% lower than DF, and the specific distinctive features of heavy fuel engines gone into below justify the high plant costs.

The two types of engines that may operate with heavy fuel oil have already been named indirectly:

- medium speed four-stroke engines with a piston diameter of approximately 200–600 mm and a speed of 1,000 to approximately 400 rpm and a power of 500 kW to approximately 18,000 kW per engine and
- low speed two-stroke engines with a piston diameter of approximately 250–900 mm and a speed of approximately 250–80 rpm and a power of 1,500 to approximately 70,000 kW per engine.

Apart from the processing (see Sect. 4.3.2) absolutely necessary for reliable heavy fuel oil operation, other distinctive features set heavy fuel oil operation apart from gas oil operation, namely the:

- risk of high temperature corrosion of the components surrounding the combustion chamber because of the fuel's vanadium and sodium content,
- risk of low temperature corrosion when the dew point is exceeded because of the fuel's sulfur content and the combustion gas' water content,
- risk of increased wear through abrasion because of the solid coke, sand and rust residues and catalyst residues as well as asphaltenes and water remaining in the fuel,
- risk of unacceptable deposits of combustion residues on combustion chamber components and in the exhaust lines and the exhaust gas turbine,
- risk of sticking, lacquering and congealing of fuel injection system components,
- risk of lubricating oil contamination through fuel leaks in injection pumps, nozzles and nozzle holders,
- risk of lubricating oil contamination because of insufficient combustion quality resulting in unreasonably short filter service life,
- risk of corrosion of the main and connecting rod bearings resulting from the fuel's reaction with the lubricating oil and
- risk of the formation of deposits in cooling ducts cooled with lubricating oil and the resultant diminished dissipation of heat, likewise as a result of the fuel's (asphalt content's) reaction with the lubricating oil.

4.3.3.2 Effects on Engine Components

Injection Equipment

Heavy fuel engines are equipped with single injection pumps. Common rail heavy fuel systems are in the implementation phase (see Sect. 18.3).

Injection equipment comes directly into contact with the preheated heavy fuel oil. Depending on the viscosity grade of the heavy fuel oil used, the preheating temperature is as high as 160°C to ensure the injection viscosity is the 12 cSt desired (see Fig. 4-32). This relatively high temperature level alone makes it necessary to solve several problems. Sealing elements such as O-rings have to be suitable. Plunger and pump cylinder clearance have to be appropriately designed to operate without seizing under higher temperature on the one hand and to ensure that leak rates are still permissible when switching to cold gas oil on the other hand.

Furthermore, specially heat treated materials have to be used for the injection elements to isolate unacceptable structural transformation resulting from the increased fuel temperature and to prevent pump seizing.

Other distinctive features of injection pumps are measures that prevent sticking and lacquering such as:

- Fuel rack lubrication: Separate lubrication protects the fuel rack and control sleeve from the ingress of fuel and keeps them clean and running smoothly.
- Leak fuel removal in the suction chamber: A circular groove in the piston guide and a connection to the suction chamber remove leak fuel in the fuel cycle.
- Leak fuel removal from the pump: Another groove in the piston guide collects the remaining leak fuel, which an additional connection to the pump conducts into the leak fuel tank.

In addition, leak oil and leak fuel must be prevented from reaching the engine's crankcase through the pump drive. Therefore, these leak quantities are trapped separately and also conducted back to the leak fuel tank through a leak oil line.

Another distinctive feature of heavy fuel oil operation is injection nozzle cooling to prevent carbonaceous deposits on the nozzle holes. This is done with a separate cooling circuit with supply and discharge through the nozzle holder. Lubricating oil, gas oil or water is employed as the coolant.

For trouble free operation, the heavy fuel oil in the injection system must be unable to cool down when the engine stops and block the injection pump for instance. The heated heavy fuel oil continues circulating through the engine when it is stopped for shorter periods. In order to start a cold engine without any problems, it has to be switched over to gas oil and then run "clean" before being shut down.

Figure 4-34 presents an example of an injection pump for heavy fuel oil operation.

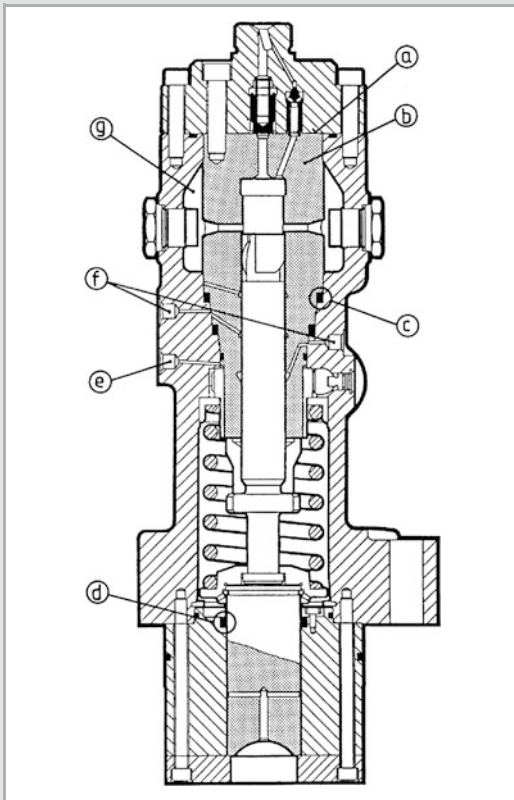


Fig. 4-34 Heavy fuel oil injection pump with fuel rack lubrication and leak fuel removal; blind hole element for high injection pressure (L'Orange). (a) Only a high pressure sealing face; (b) rigid monoelement for high pressures in heavy fuel oil operation; (c) special sealing elements for all types of heavy fuel oil; (d) central tappet with a hydraulic seal to protect the engine lubricating oil against fuel contamination; (e) scavenging connection for the governed range; (f) dual drainage for good sealing against heavy fuel oil; (g) large suction chamber – low pressure amplitudes to protect heavy fuel oil equipment on the low pressure side

For the heavy fuel oil to be distributed optimally in the combustion chamber and ignite well, it must be injected at very high pressure and finely atomized by many nozzle holes of small diameter. A medium speed engine with the following data serves as an example:

- brake mean effective pressure $p_e = 27$ bar (or $w_e = 2.7$ kJ/dm³)
- injection pressure $p_E = 1,800$ bar
- number of holes $z = 10\text{--}14$

Turbocharging

Several specific factors must be considered when turbocharging heavy fuel engines.

The engines generally run with an excess of air so that the air/fuel ratio is $\lambda_v > 2$ in every operating state to prevent high temperature corrosion. Principally induced by the correspondingly high charge air pressure, the high air flow rate lowers the temperature during combustion and thus also at the components surrounding the combustion chamber. This prevents sodium-vanadium compounds from depositing as liquid ash, which causes high temperature corrosion. The critical temperature in valve seats, above which ash deposits, is approximately 450°C. Thus, maintaining a sufficient safety margin is essential. Along with corrosion damage in the valve seat, which causes the valve disk to break in the final stage, corrosion damage on the underside of the valve must be prevented by keeping component temperatures sufficiently low.

A larger air flow rate is also beneficial for the exhaust temperature at the turbine inlet. Temperatures significantly below 550°C prevent deposits of combustion residues in the turbine and thus a drop in turbine efficiency as well as boost pressure and air flow rate. Otherwise, the combustion chamber temperature and thus the risk of high temperature corrosion and, in turn, deposits in the turbine would increase.

This self-reinforcing effect and its adverse effects must be prevented at all costs. Therefore, both the compressor and the turbine must be cleaned at regular intervals. At reduced power, a special device sprays water into the turbine inlet so that deposits flake off the nozzle ring and rotor.

Special fuel consumption standards apply to heavy fuel diesel engines. Hence, the requisite boost pressure and air flow rate may not be obtained by increasing gas exchange losses (piston work), i.e. maximum efficiency is required from the exhaust gas turbocharger. This is the only way to generate high boost pressure at low exhaust back pressure (before the turbine). At the same time, a good scavenging gradient is produced during valve overlap. This is a prerequisite for low component temperatures and contaminant free operation of the gas exchange elements.

Among other things, supercharging also determines the capability to operate at part load with heavy fuel oil. This is addressed in detail in [4-26] (see Sect. 2.2.3.4).

Thermal Efficiency and Fuel Consumption

A combustion chamber's design codetermines mixture formation and combustion and ultimately determines an engine's capability to reliably burn heavy fuel oil in continuous operation. High efficiency requires rapid combustion of the prepared mixture and consequently a compact combustion chamber with a high compression ratio (see Fig. 4-35).

Uniform distribution of the fuel throughout the entire combustion chamber is essential. Four-stroke engines accomplish this with a maximum number of fuel sprays targeted far outwards. Two-stroke engines have several injection nozzles distributed on the periphery. Fuel droplets should be as fine as possible. Injection pressure and small nozzle bores achieve this.

High Temperature Corrosion

Low combustion temperatures and intensive, steady cooling of components prevent high temperature corrosion on the components surrounding the combustion chamber. Among other things, the shape of the piston crown, the direction of spray and number of spray jets and the type of air movement (intake port) additionally influence the temperature of the exhaust valves.

Low Temperature Corrosion

Basically, low temperature corrosion can attack the cylinder liner, piston rings and ring grooves. A gentle combustion pressure curve and sufficiently high component temperatures at the pertinent points can help prevent such corrosion. Hence, an appropriate temperature profile for the cylinder liner is particularly important.

Cylinder Liner Wear and Oil Consumption

To keep cylinder liner wear low in the area of the gusset and thus assure lubricating oil consumption is low over a long period, hard oil coke that induces wear must be prevented from depositing on the piston crown. This is done by cooling the piston crown well and limiting its clearance to the cylinder liner. Furthermore, the piston edge is elevated to protect the cylinder wall so that the fuel sprays do not strike the cylinder bore surface. This may limit the direction of spray.

Flame or calibration rings arranged in the upper region of the cylinder liner are another means to reduce wear. The smaller diameter of the calibration ring and piston in this region is intended to prevent the coke deposited on the piston top land from abrading the cylinder liner's contact surface during the piston's upward stroke (see Fig. 4-35).

In addition, the mating of liner and piston ring materials decisively influences a cylinder liner's wear performance. Hardened liner surfaces (nitriding, induction hardening, laser hardening) are combined with piston ring coatings, e.g. chrome, chrome-ceramic and plasma coatings.

Constant oil consumption requires that pistons' ring grooves retain their original geometry over long periods. The distinctive feature of heavy fuel pistons is the placement of the hardened compression ring grooves in the composite piston's steel crown.

Compression Ratio

The ignition performance of occasionally ignition resistant heavy fuel oils can be positively influenced by fuel droplets on the injection side as well as by a maximum final compression temperature with a correspondingly high final compression pressure. This entails selecting a high compression ratio for the combustion chamber. As the stroke/bore ratio increases, ϵ values of approximately 13–16 are common for medium speed engines and values of 11–14 for low two-stroke speed engines.

Since, as the compression ratio increases, the air density in the combustion chamber increases when ignition is applied, the temperature peaks of the fuel gas drop at the sources of ignition. Furthermore, the pressure curve and rate of heat release can be shaped more smoothly as the compression ratio increases. This reduces nitrogen oxide emission. Thus, a high compression ratio is also beneficial for emission performance.

The aspects of combustion chamber design chiefly illustrated here with the example of a four-stroke engine, necessitate various compromises, which are easier to strike, the larger the engine's stroke/bore ratio is. Hence, modern medium speed four-stroke engines have relatively large stroke/bore ratios of up to $s/D = 1.5$ (see Fig. 18.35).

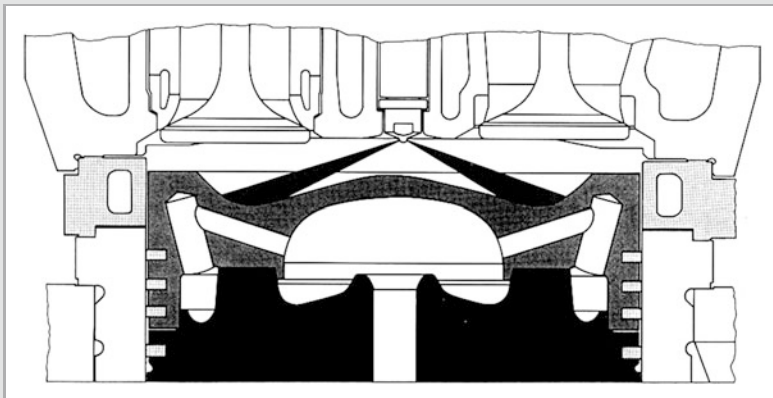


Fig. 4-35

A heavy fuel engine's combustion chamber

The rationale behind present day low speed two-stroke engines' extremely long strokes ($s/D \approx 4$) has less to do with their suitability for heavy fuel oil than efforts to run engines or propellers at minimum speed at the same mean piston velocity. This allows a maximum propeller diameter and thus maximum efficiency.

4.3.4 Running Properties of Heavy Fuel Engines

4.3.4.1 Ignition and Combustion Performance

The ignition and combustion performance of diesel engines that run on heavy fuel oil continues to be the subject of numerous research studies, the majority of which are cited

in [4-25]. Fuels with a high percentage of aromatics have particularly proven to cause ignition difficulties. Given their molecular structure, aromatics resist thermal splitting in diesel engines far more than paraffins, olefins and naphthenes.

If the engine is not modified, then large ignition delays occur when fuels containing aromatics are burned. High slopes in the cylinder pressure curve are the consequence. In the extreme case, "detonating" combustion with mechanical and thermal overloading is observed [4-27, 4-28].

Thus, problem fuel must be identified to prevent engine damage. Aromatics' property of high density with low viscosity can be drawn on to do so. Empirical values served as the basis for Fig. 4-36, which provides information on the reliability of a fuel as a function of density and viscosity.

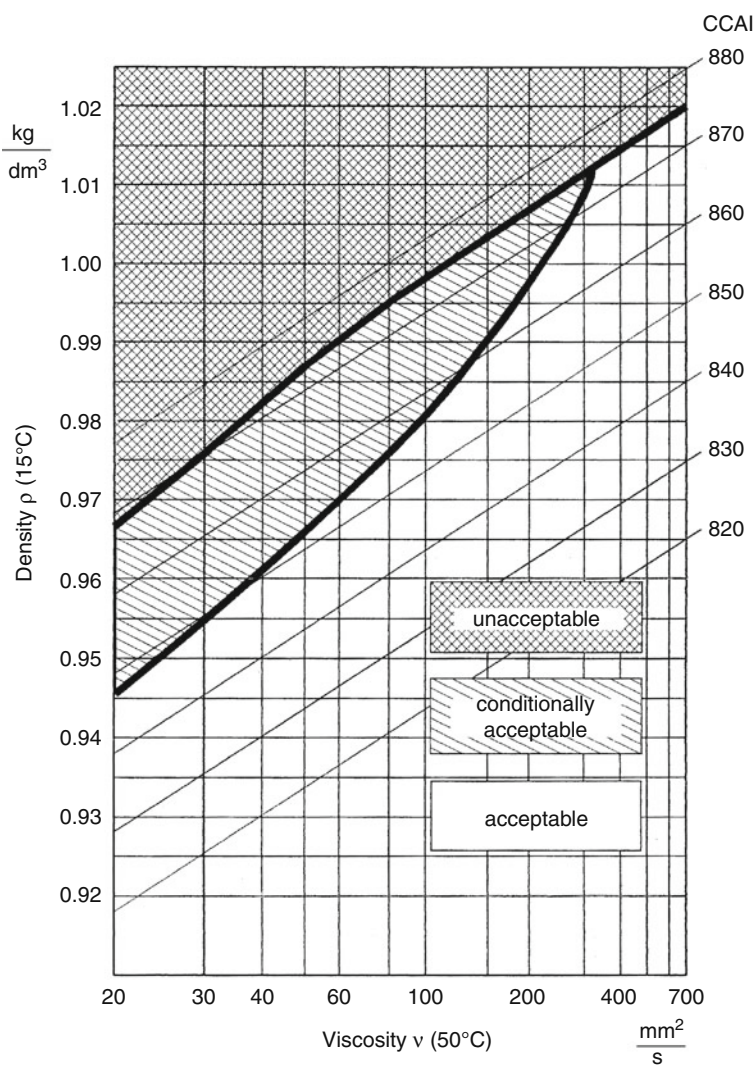


Fig. 4-36

Acceptability of fuels as a function of density and viscosity (according to the MaK operator manual)

The calculated carbon aromaticity index (CCAI) is a useful indicator for estimating ignition performance from density ρ (in kg/m^3 to 15°C) and viscosity ν (in mm^2/s at 50°C) and is calculated with the following empirical relationship:

$$\text{CCAI} = \rho - 141 \log \log (\nu + 0.85) - 81.$$

Generally, a higher CCAI translates into poorer expected ignition performance.

In the vast majority of cases, heavy fuel oils do not present any problems for commercial combustion systems. The cylinder pressure curve for a modern medium speed engine only varies slightly when gas oil and heavy fuel oil are burned. The ignition delay for heavy fuel oil operation tends to be slightly larger and the maximum pressure somewhat lower.

The rate of heat release (Fig. 4-37) also differs only slightly. The start of combustion is delayed somewhat and the end of combustion is the same within the accuracy of evaluation. Even the maximum rates of combustion hardly vary.

4.3.4.2 Emission Performance

Heavy fuel engines are basically used as main and auxiliary marine engines and as stationary engines to generate electricity in countries with underdeveloped infrastructures and must be compliant with the emission regulations of the International Marine Organization (IMO) or the World Bank, which frequently finances stationary diesel power stations.

The IMO limit for nitrogen oxide emission is:

$$\text{NO}_x = 45 \cdot n^{-0.2} \quad \text{in g/kWh,}$$

n being the engine speed in rpm.

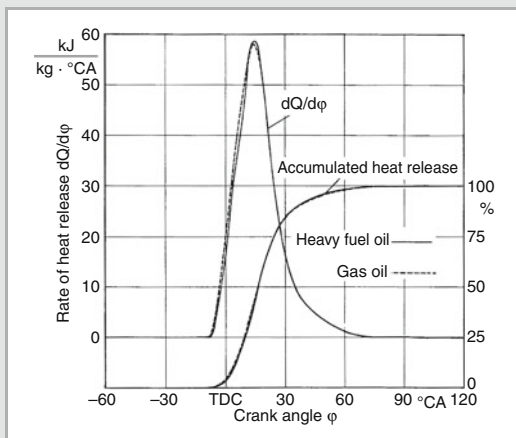


Fig. 4-37 Rate of heat release and accumulated heat release in gas oil and heavy fuel oil operation

The limit is constant in the speed range below 130 rpm (in two-stroke engines). The emission value ensues from weighting measurements in four power points according to ISO 8178-4. Preparations are underway to tighten the regulation and presumably lower the limit by 30%.

The IMO does not specify a limit for particulate emission. A requirement is imposed on ship operators based on invisible smoke emission, which corresponds to a Bosch smoke number of $\text{SN} < 0.5$.

The World Bank's limit for nitrogen oxide emission is:

$$\text{NO}_x = 940 \text{ ppm}$$

with 15% oxygen in the exhaust. A cut ($\text{NO}_x = 710 \text{ ppm}$) is planned here too.

The World Bank's limit for particulate emission is $\text{PM} = 50 \text{ mg/m}^3$.

In-engine measures that prevent nitrogen oxide emission in order to comply with the aforementioned limits are predominantly aimed at lowering the temperature level of the combustion gas during the formation of NO_x . Examples include high boost pressure, retarded start of delivery, high compression ratio, shaped and, where necessary, split injection and valve timing to apply the Miller cycle.

On the other hand, a reduction of visible smoke and particulates necessitates an increase of the fuel gas temperature in the critical operating range.

The more stringent emission requirements become, the more difficult it is to resolve the conflict between NO_x emission and particulate emission. Hence, engine manufacturers are also implementing variable injection systems that are suitable for heavy fuel oil operation, e.g. the common rail system and variable valve timing.

Other very effective measures that reduce particulate emission include lowering lubricating oil consumption and employing heavy fuel oil with low sulfur content.

The exhaust gas opacity and particulate emission (soot) of heavy fuel oil combustion is distinctive:

Using the filter paper method BOSCH designed for small vehicle engines (see Sect. 15.6.2.4) to determine exhaust gas opacity usually produces a very low value far below 1 for large diesel engines, inviting the assumption that the soot production is correspondingly low. Measurements taken on behalf of the FVV (Research Association for Combustion Engines) demonstrated that the low soot emission inferred only applied to operation with normal gas oil. The BOSCH smoke number SN is meaningless for heavy fuel oil operation (see Fig. 4-38).

The dust emission according to VDI 2066 is many times greater than the "soot emission" calculated from the smoke number SN by means of a correlation. The particulate emission measured according to ISO 8178 and resembling pollutant input indicates correspondingly high air pollution. The fuel's sulfur content is a fundamental influence because particulate emission increases approximately linearly with the sulfur flow in the engine.

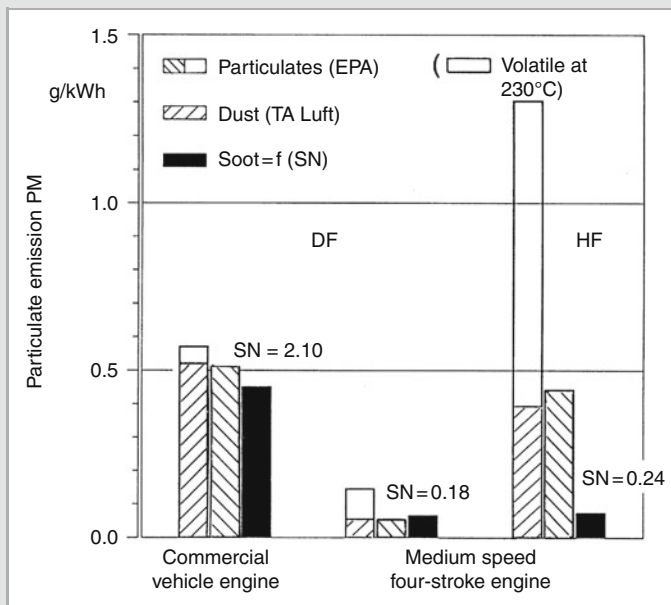


Fig. 4-38

Smoke number SN and the soot emission calculated with the SN, dust emission based on *TA Luft* and particulate emission measurement taken in conformance with the EPA. Medium speed engine ($s/D = 320/240$ mm/mm) at full load with gas oil (DF) and heavy fuel oil IF 380 (HF) compared to the full load values of an older model truck engine

Consequently, in addition to improving combustion, limiting heavy fuel oil's sulfur content like diesel fuel's (see Sect. 4.1) would seem the obvious course to pursue. In an initial step, the IMO has limited the sulfur fraction to 4.5% worldwide and to 1.5% for the Baltic Sea, the North Sea and the English Channel. As of 2010, auxiliary diesel engines for onboard power supply shall only be allowed to be run in harbors with fuels with a maximum sulfur fraction of 0.1%.

4.3.5 Lubricating Oil for Heavy Fuel Engines

The use of heavy fuel oil in diesel engines necessitates the use of engine lubricating oils specially developed for them.

Two fundamentally different engine designs are distinguished when defining the requirements for these oils:

Two-stroke crosshead engines have separate lubrication systems for the cylinder area and the crankcase because of the seal created by the piston rod stuffing box; the cylinder and crankcase in trunk piston engines are interconnected.

A crosshead engine's separate cylinder lubrication is pure loss lubrication, i.e. the cylinder lubrication system constantly replenishes the quantity of oil consumed. The cylinder oil must have the following qualities to perform or support the following important functions:

- good wetting and distribution capacity to ensure uniform distribution on the cylinder surface,
- high neutralization capacity to prevent corrosion resulting from the high sulfur content in the fuel,
- high cleaning capacity (detergent effect) to prevent deposits of combustion residues,

- high oxidation and thermal stability to prevent products from lubricating oil decomposition with attendant deposits and
- high load bearing capacity to prevent high wear and risk of seizing.

Measured in milligrams of potassium hydroxide per gram of lubricating oil (mgKOH/g), the Total Base Number (TBN) is applied as a measure of a lubricating oil's neutralizing capability.

Typical cylinder oils for crosshead engines have viscosities of SAE 50 and TBN values of 70–90.

Oils with comparatively low doping, a viscosity grade of SAE 30 and a TBN of approximately 6 mgKOH/g serve as engine oils for crosshead engines.

Unlike crosshead engines, *four-stroke trunk piston engines* have no partition between their cylinders and crankcases. Hence, aggressive combustion gases constantly load the lubricating oil in trunk piston engines. Acids, coke and asphalt-like residues load the lubricating oil together with abrasive solids from heavy fuel oil combustion, especially when specific quantities of circulating oil are low (i.e. relative to power output) and the consumption of lubricating oil is low (low refill quantities). Apart from the quality of the fuel, the loading of lubricating oil is significantly influenced by the operating conditions to which engine maintenance, the piston rings' sealing effect and the lubricating oils' processing contribute. In addition, the oil fill is normally not changed, i.e. it must perform its functions over many thousands of operating hours.

This generates the following requirements for trunk piston engine oil compatible with heavy fuel oil:

- high oxidation and thermal stability to prevent the oil from causing lacquering and coke-like deposits,
- high neutralization capacity of acidic combustion residues to prevent corrosion,
- particularly good cleaning and dirt suspending capacity (detergent/dispersant effect) to neutralize the coke and asphalt-like combustion residues, which increasingly form,
- particularly careful matching of the detergent/dispersant additives in order to effectively clean the lubricating oil in separators and filters as required and
- low propensity to emulsify and low sensitivity of the active ingredients to water to maintain effective oil care and prevent premature losses of additives.

In addition, high requirements are imposed on its load bearing capacity, good foaming tendency and low propensity to evaporate.

Typical lubricating oils for trunk piston engines powered by heavy fuel oil have viscosities of SAE 40 and TBN values of 30–40.

4.4 Fuel Gases and Gas Engines

4.4.1 Historical Review

Precursors of present day gasoline engines, the first combustion engines were spark ignited gas engines that utilized generator gas or city gas obtained from coal or wood as fuel gas. The brake mean effective pressures and efficiencies attained in those days were modest. An easier to store liquid fuel, gasoline was used only later as vehicles began being motorized. With that, the gas engine, only still in use on a small scale as a stationary engine, e.g. in iron and steel works to recover blast furnace gases, disappeared from collective memory. Rudolf Diesel [1-3] initially also envisioned gas operation for his new rational heat engine. This prompted

Krupp along with MAN to acquire an interest in the construction of a test engine. More recent tests on the use of hydrogen in large diesel engines have made Diesel's idea timely again.

The gas engine has been able to catch up with the diesel engine, specifically to generate power in cogeneration units, only by fully taking advantage of lean burn combustion's potential to reduce exhaust emission (see Sect. 14.2 for more on CHP).

4.4.2 Fuel Gases, Parameters

4.4.2.1 Fuel Gases for Gas Engines

Table 4-10 contains the most important fuel gases used in gas engines with their characteristic combustion values. The pure gases solely appear in gas mixtures such as natural gases. Only hydrogen H_2 can be used as pure gas, provided it is available. Landfill and digester gas are some of the renewable fuel gases produced when biomass, e.g. feces, garden cuttings or straw, decomposes. This relieves the environment in two ways: Their release is prevented and their use conserves fossil fuels. Their basic constituents are 40–60% methane and carbon dioxide. In addition, they may also contain harmful substances, e.g. chlorosulfide, fluorosulfide und hydrogen sulfides, which can be removed from the environment when these fuels are burned. In principle, the same combustion characteristics used to calculate combustion with liquid fuels apply to gases (see Sect. 1.2.3.1). However, the gas volume in m^3_n under standard conditions is often selected as the reference value.

The hydrocarbons contained in natural gas are mostly paraffins (aliphates) with chain-like configurations of C and H atoms and the structural formula C_nH_{2n+2} . The simplest hydrocarbon, methane CH_4 is followed by ethane C_2H_6 , propane C_3H_8 and butane C_4H_{10} . Like methane, they are gaseous under standard conditions. Called isomerism, the alteration of the molecules' chain-like structure already appears in butane. Thus, the physical properties of isobutane

Table 4-10 Parameters of the most important fuel gases relative to the volume of gas under standard conditions (Table 3-5, 2nd Ed.)

Type of gas	Calorific value H_u kWh/m^3_n	Minimum air requirement L_{min} m^3/m^3	Calorific value of the air/fuel mixture h_u kWh/m^3_n	Methane number MN –
Methane	9.97	9.54	0.95	100
Natural gas L	9.03	8.62	0.93	88
Natural gas H	11.04	9.89	0.96	70
Propane	25.89	23.8	1.03	34
N-butane	34.39	30.94	1.03	10
Landfill gas	4.98	4.73	0.86	>130
Digester gas	6.07	5.80	0.89	130
Coke ovengas	4.648	4.08	0.91	36
Carbon monoxide	3.51	2.381	1.038	75
Hydrogen	2.996	2.38	0.89	0

Table 4-11 Influence of isomerism on the characteristic combustion data of butane (Table 3-6, 2nd Ed.)

C_4H_{10}	λ_u Percentage of gas in air by volume	λ_o Percentage of gas in air by volume	Auto-ignition temperature K	Molar mass kg/kmol	Density kg/m^3_n	Boiling point at 101.325 kPa K
Isobutane	1.8	8.4	733	58.123	2.689	261.43
N-butane	1.9	8.5	678	58.123	2.701	272.65

change from the standard form (n-butane) while the molar mass remains identical (see Table 4-11). These factors must be allowed for, especially when chemical waste gases are utilized in gas engines.

4.4.2.2 Combustion Parameters

Calorific Value and the Calorific Value of the Air/Fuel Mixture

Butane's calorific value of $H_u = 34.4 \text{ kWh/m}^3_n$, is the highest among the fuel gases used in gas engines (see Table 4-10). A single gas, hydrogen has the lowest calorific value of 2.99 kWh/m^3_n . The difference in these single gases' calorific value corresponds to a factor of more than 11. Mixing them with inert gases, e.g. carbon dioxide CO_2 or nitrogen N_2 , further increases this difference. The "weakest" low energy content gas mixtures that gas engines are still able to utilize have calorific values of around 0.5 kWh/m^3_n with a sufficient H_2 fraction, i.e. the ratio of the calorific values of "poor gas to rich gas" can be as high as 1:60. These differences in calorific value result from the differing C and H^2 fractions, which also affect the differences when stoichiometric combustion has a minimum air requirement L_{min} . By contrast, pairing H_u and L_{min} causes the calorific values of the air/fuel mixture $h_u = H_u/(1 + \lambda_v L_{min})$, which are determinative for the energy yield, to display a rather uniform pattern of values with only slight differences.

Methane Number MN

The methane number MN is defined by the volumetric mixture ratio of methane ($MN = 100$) and hydrogen ($MN = 0$) and thus directly furnishes information on a gas mixture's detonation limits. A methane number near 100 signifies high detonation limits, a methane number near zero low detonation limits. Accordingly, a mixture of 20% hydrogen H_2 and 80% methane CH_4 has a methane number of 80. Cartellieri and Pfeifer, who simultaneously also determined the methane number of other gases and gas mixtures in tests on a one cylinder CFR test engine, formulated their definition at an air/fuel ratio of $\lambda = 1$ [4-29].

The methane number in three-component gas mixtures can be determined with the aid of ternary diagrams, which also contain parameter lines of constant methane numbers for the lines of the constant gas fraction. Figure 4-39 illustrates the method of reading such a diagram: Point P in the diagram to the left represents the mixture for the percentage fraction a, b and c of the three components A, B and C. The diagram to the right additionally contains the line of constant detonation limits or the methane number passing through P.

Figure 4-40 is a ternary diagram of the composition of digester gases' three main components methane, carbon dioxide and nitrogen with the resultant methane numbers.

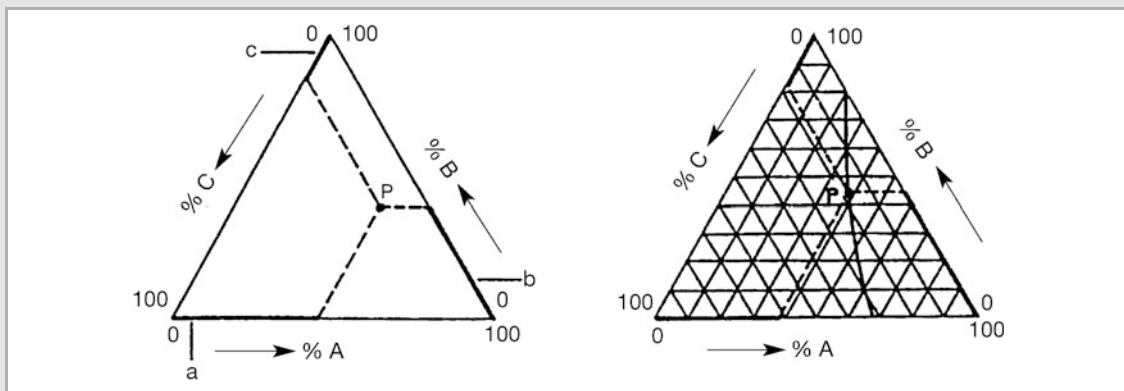
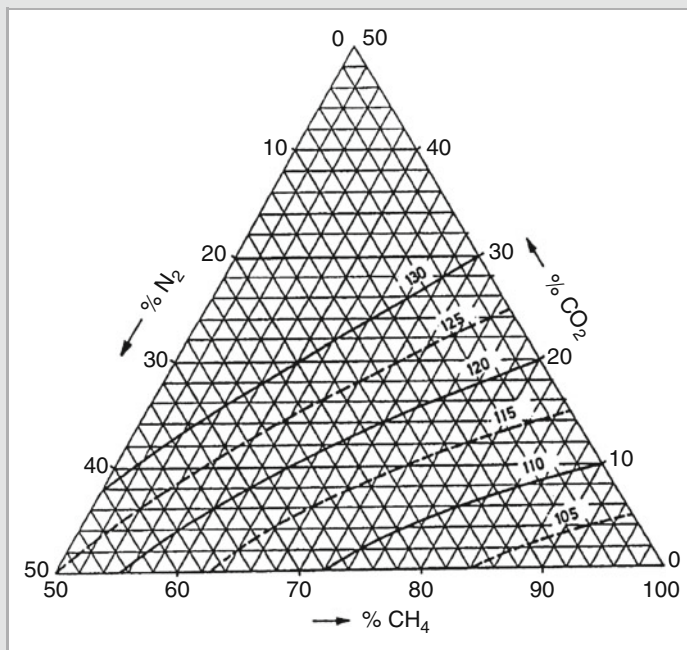


Fig. 4-39 Plotting of a ternary diagram to determine the methane number for a mixture of three gases [4-30]

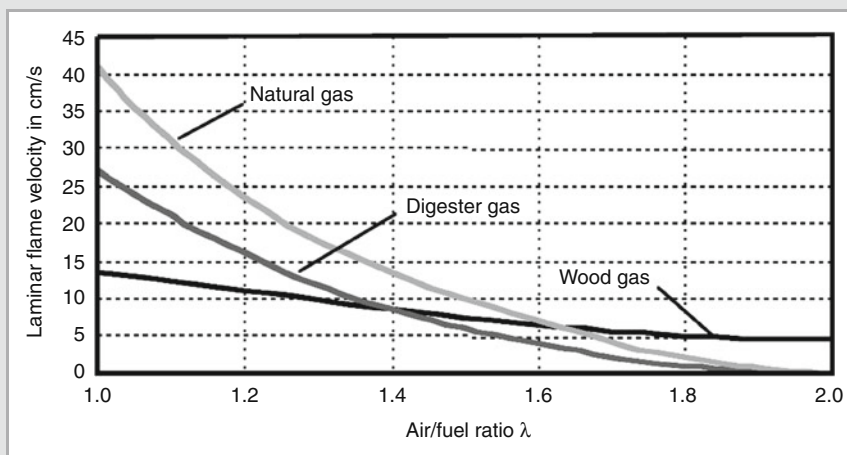
**Fig. 4-40**

Ternary diagram for digester gas composed of methane, carbon dioxide and nitrogen [4-30]

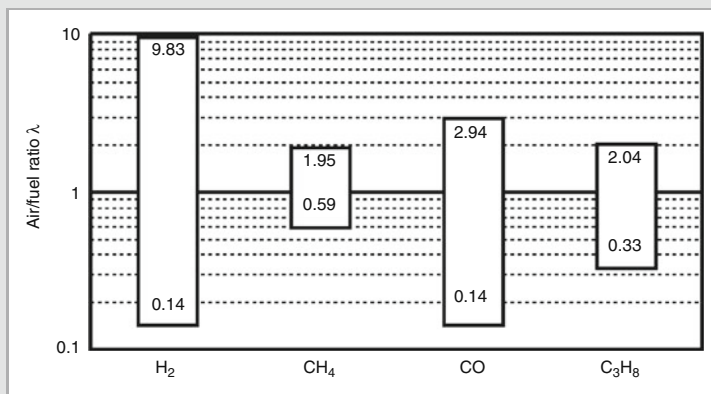
Various manufacturers sell programs that compute the methane number. The program developed by AVL is primarily used in Europe [4-30]. Contingent on the operating point's H₂ content, it can shift toward the "lean" side when applied to hydrogen gas mixtures. However, since the computation is based on an air/fuel ratio of $\lambda = 1$ it fails to state the detonation characteristics correctly.

Laminar Flame Velocity

Laminar flame velocity specifies the velocity with which the flame propagates in laminar flow conditions. It is largest in the range of stoichiometric conditions and decreases as the mixture is increasingly leaned as well as enriched ($\lambda < 1$). The individual fuel gases behave differently (see Fig. 4-41).

**Fig. 4-41**

Influence of the air/fuel ratio λ on laminar flame speed in cm/s

**Fig. 4-42**

Ignition limits of the pure gases hydrogen H₂, methane CH₄, carbon monoxide CO and propane C₃H₈

Ignition Limits

Single gases' ignition limits strongly influence fuel gases' mixture formation (Fig. 4-42). They specify the hypostoichiometric or stoichiometric air/fuel ratios at which ignition can still occur. Hydrogen has the broadest ignition limits, methane a relatively small ignition range. Hence, it is important to understand the processes during mixture formation in order to be able to implement appropriate measures for ignition in the combustion chamber. The requirements for mixture formation or the fuel admission system are rather moderate when hydrogen is used as fuel. Particularly high demands are made on the homogeneity of a natural gas mixture, above all for extremely lean operation.

4.4.2.3 Evaluation of Gas Quality

The quality of a gas intended for gas engines is evaluated primarily on the basis of the air/fuel mixture's calorific value and the methane number. While the calorific value of the air/fuel mixture defines a gas system's design (gas pressure and gas valve opening duration), the methane number determines the detonation limit and thus the maximum engine power.

Gases from different sources are blended together to ensure reliable gas delivery. Natural gas is blended into the base gas according to the allowable limits of the gas family. As a rule, gases are blended (usually a propane/butane gas mixture) in such a way that either the calorific value of the air/fuel mixture or the Wobbe index (characteristic value of the thermal load of gas burners) is constant. Even when the air/fuel mixture's calorific value is constant, this distinctly changes the methane number. Smooth engine operation without detonating combustion and resultant engine damage requires keeping the distance to the detonation limit sufficiently large. The losses of efficiency and power this causes are prevented by active detonation control, thus

making it possible to operate an engine at the detonation limit under optimal conditions and at maximum engine efficiency.

4.4.3 Definition and Description of Gas Engines

4.4.3.1 Classification of the Combustion Systems

The combustion systems employed in gas engines are derived from the air/fuel mixture's type of gas blending and type of ignition. The generally accepted definition of combustion systems allows a division into spark ignited (SI) engines, dual fuel (DF) engines and gas diesel (DG) engines (Fig. 4-43).

Both SI and DF engines operate based on the gasoline engine system. Only their type of ignition differs. However, the heterogeneous mixture in gas diesel engines is ignited by auto-igniting the fuel gas with the aid of a small quantity of diesel fuel (pilot fuel) and thus corresponds to the diesel engine system.

Spark Ignited (SI) Engines

Based on the system of the gasoline engine, the homogeneous air/fuel mixture of spark ignited engines is produced outside the combustion chamber [4-31]. The mixture may form centrally in the engine air intake as well as after the compressor or before every intake valve in supercharged engines. Consequently, the requisite gas pressure must be higher than the intake air pressure or the charge air pressure.

A spark plug initiates ignition electronically. Glow plug ignition for prechamber engines might also be conceivable but would require a controlled supply of gas into the compressed mixture in the prechamber to trigger ignition [4-32]. Engine power is determined by the mass of the air/fuel mixture supplied and thus quantity-controlled.

The compression ratio in production diesel engines routinely used as SI engines must be adjusted to the detonation

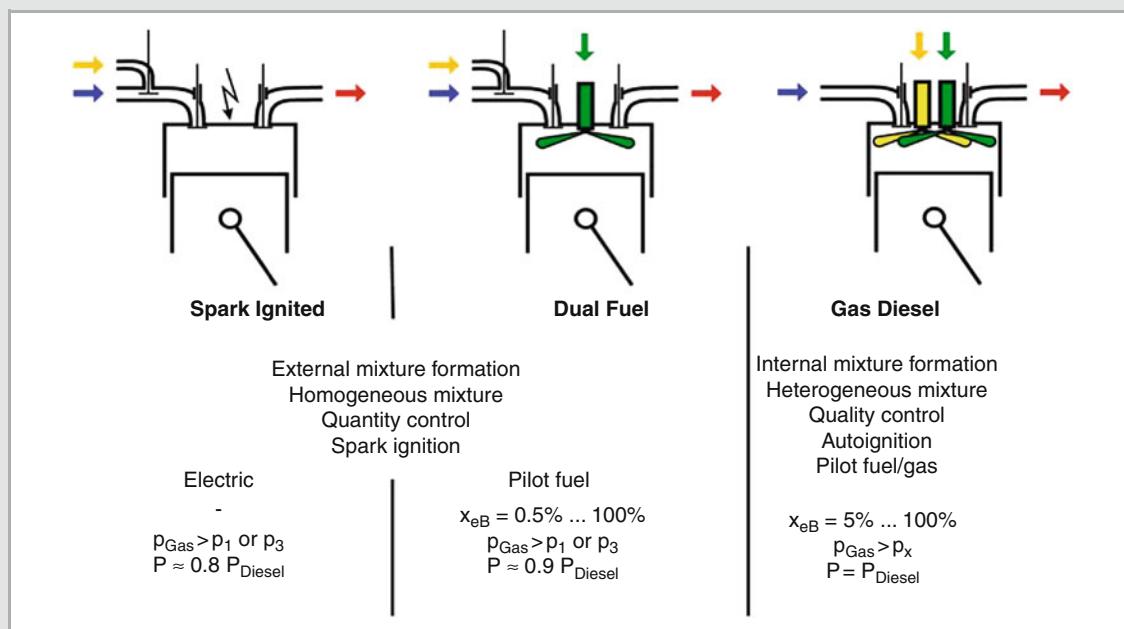


Fig. 4-43 Definition of the combustion process in gas engines

limits (methane number) of the fuel gas available so that the air/fuel mixture is unable to auto-ignite. This reduces the power by approximately 20% over the diesel system.

Dual Fuel (DF) Engine

Diesel and spark ignited engines resemble one another in terms of their type of ignition and mixture formation and thus operate on the basis of the system of the gasoline engine, the fundamental difference being the type of ignition source. Unlike electric ignition in SI engines, ignition in DF engines is initiated by injecting diesel fuel, so-called pilot fuel [4-33, 4-34]. In principle, it is possible to boost the quantity of pilot fuel to 100 in order to also run the engine in pure diesel operation (dual-fuel engines). A micropilot engine limits the pilot fuel to only the percentage that starts the engine in diesel operation and the quantity of pilot fuel required, approximately 10 to 15% of the quantity injected at full load. Since its mixture preparation and delivery resemble that of SI engines, this combustion system's engine power is also determined by the mass of the air/fuel mixture supplied and thus quantity-controlled.

Since, on the one hand, the pilot fuel must auto-ignite and, on the other hand, the homogeneous air/fuel mixture that delivers the main energy for engine operation may not tend to detonate, i.e. it must have a sufficiently high methane number, DF engines require a lower reduction in the compression ratio than SI engines. The application

engineering of production diesel engines does not require replacing the injection equipment in dual fuel engines with an ignition system (injection pumps) and spark plugs (injection nozzles) as in spark ignited engines.

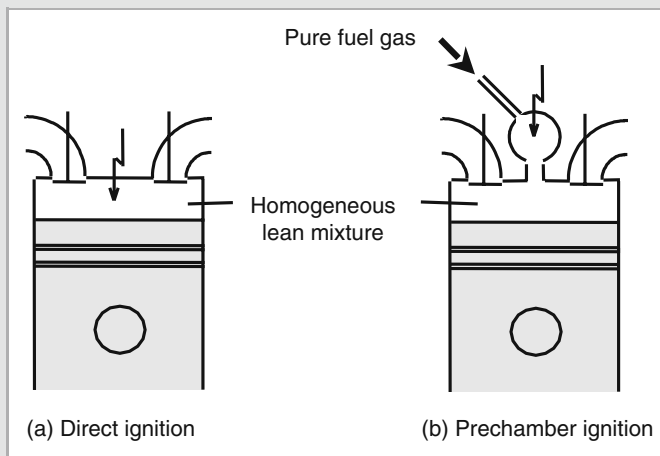
Gas Diesel (DG) Engines

Based on the system of the diesel engine, gas diesel engines are fundamentally auto-igniting, the mixture being produced by injecting the gases into the compressed combustion air. Thus, the mixture in the combustion chamber is inhomogeneous at the time of ignition [4-35]. Ignition is initiated by injecting an additional amount of diesel fuel. Engine power is only determined by the gas mass and is thus quality-controlled.

The compression ratio needs no significant adjustment to ensure the pilot fuel ignites. Thus, the same engine power can be produced as in the diesel system.

4.4.3.2 Spark Ignited (SI) Engines

Two basically different ignition concepts are distinguished, direct ignition and prechamber ignition. With a few exceptions, the direct ignition concept illustrated in Fig. 4-44a applies to high-speed engines ($n \geq 1,500$ rpm) with bore diameters of up to 170 mm. This essentially corresponds to the ignition concepts employed in car gasoline engines. At lower speed ($n = 800\text{--}1,200$ rpm) and richer combustion ($\lambda = 1$), the flame speed in the combustion chamber is high

**Fig. 4-44**

Directed ignition (a) and precombustion chamber ignition (b) in spark ignited engines

enough to even implement this concept for bore diameters of up to 250 mm. Lean burn engines ($\lambda \geq 1.7$) with bore diameters of 200 mm and larger require precombustion chamber ignition (Fig. 4-44b), i.e. the combustion chamber is divided into a main and secondary combustion chamber called the precombustion chamber, which has a volume of between 1 and 5% of the compression volume. The precombustion chamber has its own gas supply, which enriches the mixture in the chamber up to an air/fuel ratio in the range of $\lambda \approx 1$ to guarantee ignition.

Thus, the rich mixture from the precombustion chamber allows reliable ignition of extremely lean mixtures ($\lambda \geq 2.2$). High speed SI engines can achieve NO_x emissions that are compliant with the Technical Instructions on Air Quality Control (*TA Luft*) in the range of 250–500 $\text{mg}/\text{m}^3_{\text{n}}$ with net efficiencies of over 45%.

Unscavenged precombustion chambers are also implemented in lean burn engines with bore diameters below 200 mm to enhance the ignition conditions at the spark plug (see Sect. 4.4.4.3).

4.4.3.3 Dual Fuel (DF) Engines

Auto-ignition of the injected diesel fuel, the pilot fuel, initiates the spark ignition of the gas mixture. Rudolf Diesel already proposed this system to burn difficult to ignite fuels such as coal.

The quantity of pilot fuel fundamentally influences the level of NO_x emission from dual fuel engines. Since the combustion cycle of the mixture ignited by the injection sprays nearly doubles the NO_x values (1,500–2,000 $\text{mg}/\text{m}^3_{\text{n}}$), NO_x limits can presently only be met with SCR catalysts when the quantities of pilot fuel are above 5% (dual-fuel engines). Reducing the quantity of pilot fuel (energetically) to approximately 0.5% of the full load quantity (as in micropilot engines) makes it possible to comply with NO_x values of 500 $\text{mg}/\text{m}^3_{\text{n}}$ (*TA Luft* limit) even without exhaust gas aftertreatment.

The advantage of the dual-fuel engine concept is its capability to continue running as a diesel engine should the gas run out (mainly important for emergency power applications). The engine is started as a diesel engine so that gas, as the primary energy source, can then be successively mixed into the air flow. This type of engine is chiefly used for large quantities of gas with low calorific values and low flammability, e.g. gases with high percentages of inert gas.

The relatively high methane number required is a drawback since a compression ratio must be selected, which is sufficient for the diesel fuel to auto-ignite during a start. When gases or gas mixtures have low methane numbers, countermeasures, e.g. lead reduction or “leaning”, must guarantee operation without detonation by replacing the fraction of fuel gas energy with larger quantities for pilot ignition. This is particularly problematic in hydrogen-rich synthesis gases since it means accepting either only moderate mean pressures (at the level of naturally aspirated engines) or high levels of diesel fuel consumption.

4.4.3.4 Gas Diesel Engines

The gas diesel engine concept is characterized by mixture formation in the combustion chamber. The high pressure fuel gas is upstream from the pilot ignition and then subsequently ignited by the diesel spray [4-36]. The ignition quality of the gas is of such secondary importance that this method can even use gases with low methane numbers without special measures. This development is based on the presence of such high pressure gas (approximately 200 bar) as accumulates as a “byproduct” on CNG tankers or is available in the petroleum industry on drilling platforms or in pumping stations. Since the requisite gas pressure must be higher than the final compression pressure, increased demands are placed on the gas system (compression resistance and safety).

This concept's efficiencies are practically just as high as those of diesel engines. However, the NO_x emissions of any engines operating on the basis of the pilot ignition concept require exhaust gas aftertreatment with a deNO_x catalyst.

4.4.3.5 Hydrogen Operation of Gas Diesel Engines

In the future, efforts to utilize alternative fuels and reduce environmental pollution from engine exhaust gases will attach great importance to hydrogen [4-37], provided it is not obtained by electrolysis using electrical power generated with fossil fuels. With an eye toward even being able to use hydrogen in large diesel engines at some point, pertinent tests were conducted on a single cylinder diesel engine with a piston diameter of 240 mm [4-38]. In the current stage of development, hydrogen compressed to 300 bar is supplied to the engine shortly before top dead center by an injection valve with several spray holes, which replaces the centered injection nozzle. Then, the air/hydrogen mixture auto-ignites. In the course of the tests, the compression ratio was increased from its original $\varepsilon = 13.7$ in the diesel version to 16.8–17.6. The air/hydrogen mixture's sizeable ignition range largely allows quality control comparable to load adjustment common in diesel engines. The brake mean effective pressures of approximately 19 bar corresponding to specific work $w_e = 1.9 \text{ kJ/dm}^3$ attained in test operation of a supercharged engine suggest advances may approach 25 bar in the future. This is comparable to the power level of present day marine diesel engines.

Combustion proceeds soot-free. The greenhouse gas carbon dioxide CO_2 , carbon monoxide CO and hydrocarbon compounds HC only appear in insignificantly small concentrations. Nitrogen oxides are the sole quantitatively relevant components. Their concentration exceeds the emission level of emission-optimized diesel engines. The strong inhomogeneities of the air/fuel mixture and the extremely short duration of combustion with high conversion rates, which cause local high temperatures in the combustion chamber and thus increased NO formation, can be regarded as the reasons for this. Further work on development is needed here. Aftertreatment systems that reduce NO_x , which may become necessary, function extremely effectively because of the purity of the exhaust.

Even though a hydrogen powered diesel engine remains a future option from the current vantage point, it already fulfills two of Rudolf Diesel's visions, namely smoke-free operation of his rational heat engine and its suitability for fuel gases too!

4.4.3.6 Gas Engines as Vehicle Engines

Spark ignited engines derived from diesel engines on the basis of the $\lambda = 1$ concept are used in municipal vehicles, commuter vehicles and public transportation. Such vehicles use natural gas (CNG) compressed to 200 bar carried in roof tanks. They are easily modified and handle like a vehicle designed with a diesel engine.

Systematic development toward lean burn engines ($\lambda \geq 1.7$) is opening significantly expanded options with enhanced power, efficiencies and ranges [4-39]. The demand for higher power at lower fuel consumption and minimal emissions has generated numerous changes in the basic diesel engine, e.g. combustion chamber shape, piston design, intensive cooling of cylinder head and liner, lubricating oil consumption, fuel system and engine control. Thus, today's vehicle gas engines represent independent developments [4-40].

Gas engines in industrial locomotives should now be regarded more as an exception. However, they are sporadically necessary in areas of operation with special environmental regulations.

4.4.4 Mixture Formation and Ignition

4.4.4.1 Potentials of Mixture Formation

Similar to car gasoline engines, a distinction can be made between gas engines with:

- *central mixture formation* by means of mixture-forming equipment or a gas mixer (corresponding to single-point injection) and
- *individual mixture formation* before the intake into the combustion chamber or in the engine's *combustion chamber* (corresponding to the options of multi-point injection).

The central gas mixer in supercharged gas engines may be placed before or after the supercharger group's compressor. Placement on the suction side is advantageous since it only requires low gas pre-pressure, e.g. for digester or landfill gas (30–100 mbar). The homogenization of the mixture in the compressor generates another advantage. This provides every bank in V engines an exactly equal air/fuel ratio. Placing the gas mixer on the pressure side (p_2) requires a correspondingly higher gas pre-pressure, which must be generated by an internal gas compressor case by case. In addition, there is always a risk of disruptively rich stream filaments, making it expedient to connect a homogenizing unit downstream from the gas mixer.

Individual mixture formation is found in larger engines ($D > 140 \text{ mm}$). Provided the engine is not naturally aspirated, the gas pressure level must be elevated commensurately with the charge air pressure. Additional gas intake valves are necessary in both cases. This requires design changes in the cylinder head. When a throttle is used to adjust the air supply to control the torque, the valve cross section in the gas valve must be adjusted so that the mixture continues to be ignitable. The requisite air mass flow in supercharged engines is adjusted by controlling the boost pressure with an exhaust bypass (wastegate), compressor bypass or variable turbine geometry (VTG), the torque being changed either by means of load-dependent gas pressure control or gas intake valves with variable opening durations.

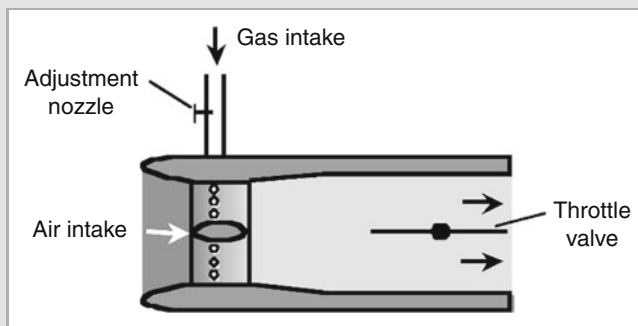


Fig. 4-45
Venturi mixer

4.4.4.2 Gas Mixers

Most gas mixers function on the basis of the venturi principle: A venturi nozzle positioned in the intake air flow lowers the stationary pressure in the narrowest cross section where two bores interconnected by a annular channel that admits gas are located (Fig. 4-45). The differential pressure in the inlet and thus the influent gas mass flow also increase as the cylinder charge increases, e.g. when speed increases. Since the densities of gas and air change simultaneously, additional control functions are necessary to maintain the desired air/fuel ratio.

A variable restriction gas mixer (IMPCO) is frequently used in engines with low emission requirements. Figure 4-46 presents its functional principle. The distinctive feature of this type of gas metering valve is its external shape, which allows obtaining a mass flow-dependent air/fuel ratio curve relatively easily. When another characteristic is desired, then the shape of the control valve is adapted to the desired mixture ratio. The spring located in the vacuum chamber provides another potential control function. This type of gas mixer may be implemented on the suction or the pressure side. Since it has no electronic actuator, the simple mechanics are a significant advantage. However, its fixed setting

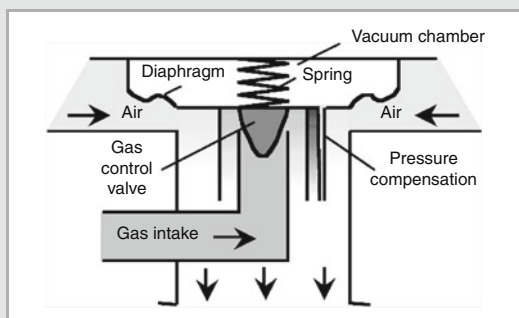


Fig. 4-46 Gas mixer: IMPCO variable restriction carburetor

corresponding to the geometry and thus a particular air/fuel ratio value when it is adjusted are a disadvantage. This concept precludes any control function to compensate for variable calorific values or changing ambient conditions (intake temperature and air pressure).

Its high flow losses and the attendant charge losses make this type of mixer unsuitable for supercharged gas engines with high specific power.

Another widespread basic concept utilizes the area ratio of the air and gas cross section to adjust the mixture ratio. Already relatively old, the underlying idea – corresponding to a variable venturi carburetor – was taken up by Ruhrgas AG in the mid 1980s and refined to its current state (with the brand name HOMIX).

The advantage of this concept for lean burn engines is the ability to regulate the air/fuel area ratio relatively easily during operation. This type of gas mixer always requires a pressure regulator (zero pressure regulator) that adjusts the pressure conditions in the gas feed to the pressure in the suction pipe before the compressor.

A so-called gas train is needed to adjust the pressure level in the gas systems to the pressure level of the mixture formation intended in the gas engine. In addition to adjusting the pressure, the gas train or “gas path” usually integrates the required safety equipment [4-41].

4.4.4.3 Electric Ignition Systems and Spark Plugs

As in car gasoline engines, the air/fuel mixture in spark ignited engines ignites with the aid of a spark plug. In use until the early 1990s, mechanically driven generator ignition units (e.g. from Altronic) have been abandoned in favor of electronic ignition in which a thyristor controls a capacitor's discharge to easily vary the ignition point, e.g. when there is a risk of detonating combustion. It is important to differentiate between the maximum potential gate-trigger voltage (gate-trigger voltage supplied) and the voltage required for arcing (gate-trigger voltage required). The amount is primarily determined by the gap size between the center and ground electrode.

The required gate-trigger voltage also increases with the charge density at the ignition point and thus with the specific work w_e (or the brake mean effective pressure P_{m_i}).

Commercially available electrodes protected with precious metals (platinum, iridium or rhodium), e.g. Champion RB 77WPC and Denso 3-1, increase the life of spark plugs in stationary engines. Some engine manufacturers also rely on internal developments.

Unscavenged Precombustion Chamber and Precombustion Chamber Spark Plugs

Since their ignition conditions strongly depend on the conditions in the combustion chamber, e.g. charge movement and mixture inhomogeneities, lean burn engines impose special requirements on ignition systems. One measure is the use of precombustion chamber spark plugs (unscavenged precombustion chambers without their own gas feed). The spark plug is surrounded by a chamber that relatively small passages (transfer bores) connect with the main combustion chamber. This establishes constant ignition conditions for the spark plug, which improve ignition conditions and thus the spark plug's life [4-42]. The mixture can be leaned out, thus producing lower NO_x emissions than in an undivided combustion chamber.

Laser Ignition

Concepts that employ a pulse laser to ignite the mixture in the combustion chamber are being developed as alternatives to electronic ignition systems with spark plugs [4-43]. Through an optical access to the combustion chamber, a fiber optic cable focuses light from a laser source anywhere in the combustion chamber in such a way that ignition of the mixture is

initiated. By virtue of the principle, its advantage is its elimination of spark plug wear. Further, several ignition sources may be implemented in a combustion chamber, thus producing extremely rapid mixture conversion rates.

Goals of development are stable optical accessibility to the combustion chamber, the minimization of power losses between the laser source and the combustion chamber and the reduction of the cost of the overall system. The latter particularly continues to hinder the use of such systems in production. The brake mean effective pressures of up to 30 bar corresponding to specific work $w_e = 3.0 \text{ kJ/dm}^3$ envisioned for future spark ignited engines are only conceivable with laser ignition.

4.4.5 Gas Engine Emissions

4.4.5.1 Combustion of Homogeneous Gas Mixtures

Presented as a function of the air/fuel ratio λ in Fig. 4-47, the emission characteristic of the regulated exhaust emissions of carbon monoxide CO, total hydrocarbons HC and nitrogen oxides NO_x is typical for the combustion of a homogeneous fuel-air mixture. While CO and HC strongly decrease as the excess air ($\lambda > 1$) increases after stoichiometric combustion, NO_x emission only reaches its maximum at $\lambda \approx 1.1$ because the temperatures in the combustion chamber connected with the oxygen supply are still very high at $\lambda > 1$. The emission level decreases when air/fuel ratios are increased further, reaching a level in the extreme lean range at $\lambda \approx 1.6$, which is acceptable for the emission control legislation in *TA Luft*.

The boundaries in the figure indicate the two types of operation for an emission-optimized gas engine: combustion of a stoichiometric ($\lambda = 1$) or a lean air/fuel mixture with $\lambda \geq 1.6$.

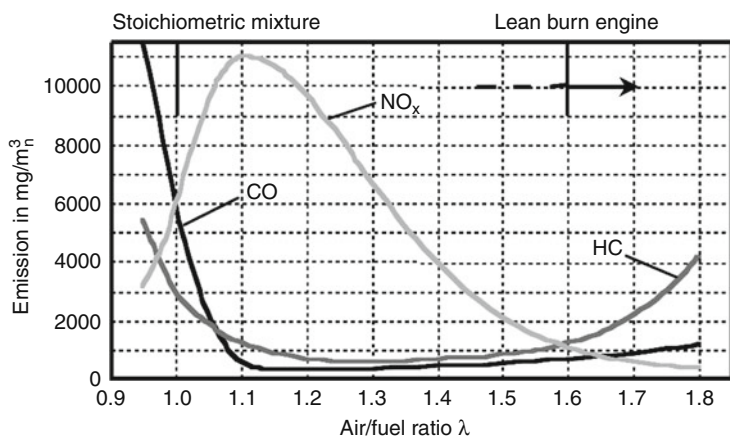


Fig. 4-47

Air/fuel ratio and exhaust emission, limits of the concept for NO_x reduction

European emission control legislation is essentially oriented toward Germany's *TA Luft* (see Sect. 15.2) with the noteworthy distinction that, instead of referring to power as is often common, the limits refer to the charge flow rate in m^3_{n} with an O_2 content of 5% in exhaust. Thus, the amount of power generated from the same quantity of fuel gas is inconsequential since the efficiency of utilization does not enter into the calculated emission values. Therefore, individual countries such as Denmark factor in net efficiency when establishing their limits for unburned hydrocarbons. Emission limits not only exist for NO_x , CO and HC but also non-methane hydrocarbons (NMHC), dust or particulate emission (based on stipulated measuring procedures, see Sect. 15.6) and C compounds classified as C_1 , C_2 , C_3 , etc. as well as dioxins and furans.

4.4.5.2 Gas Engines with Stoichiometric Mixtures

As in car gasoline engines, a stoichiometric air/fuel ratio is the prerequisite for use of a three-way catalyst that simultaneously lowers CO, HC and NO_x emission by post-oxidation or reduction. The air/fuel ratio must be controlled with a lambda oxygen sensor that ensures the catalyst functions within the very narrow limits of the "lambda window" of 0.980–0.991. Only hypostoichiometric combustion ($\lambda \approx 0.997$) can effectively reduce NO_x .

In conjunction with the influences generated by oil ash and the problem gases contained in the fuel gas, the high thermal load diminishes catalyst efficiency. Hence, servicing and maintenance costs are relatively high. This limits the use of three-way catalysts to engines with lower power, predominantly naturally aspirated engines ($p_{\text{me}} \leq 8 \text{ bar}$ or $w_e \leq 0.8 \text{ kJ/dm}^3$). However, a combination of exhaust gas turbocharging and exhaust gas recirculation can simultaneously lower the thermal load and raw NO_x emission and thus costs.

4.4.5.3 Lean Burn Engines

Mixture Control with a Lean Oxygen Sensor

Lean burn operation in compliance with *TA Luft* limits requires lean mixture supercharging to compensate for the losses of effective brake work connected with lean combustion by supercharging. A premixed air/fuel mixture has proven to be easily precompressible in the exhaust gas turbocharger's compressor with advantages for mixture homogenization (see Sect. 4.4.4.1). Only lean burn engines can be used for biogases loaded with such pollutants as chlorine, fluorine and silicon compounds and hydrogen sulfide H_2S since these "catalyst poisons" would render a three-way catalyst inoperable in no time.

A closed loop control maintains the requisite stability of the lean air/fuel ratio (comparable to air/fuel ratio 1 operation). The "lean oxygen sensors" employed to do this deliver an electrical signal usable by the control loop starting only at an air/fuel ratio of $\lambda > 1.6$. The sensors' limited lives,

particularly when used in biogases with extremely harmful constituents (Cl, F, S, etc.), make this concept so extremely cost intensive for an engine operating time of 8,000 h/a that alternative concepts have been developed to control mixture composition.

Alternative Concepts for Lean Burn Engines

Combustion Chamber Temperature (TEM) Measurement

Deutz's [4-44] concept envisions measuring representative temperature in a volumetric element of the combustion chamber to maintain the air/fuel ratio. The relatively slow sensor (thermocouple) does not measure the true temperature in the volumetric element, a recess in the bottom of the cylinder head. Rather, it measures a mean temperature reached during the combustion cycle, to which the average NO_x emission measured at an operating point and stored in the controller (TEM) is assigned.

The sensor's decreasing sensitivity due to isolating deposits has an adverse effect since the mixture is enriched at a pseudo excessively low average temperature. Operation at the detonation range on the other hand produces better heat transfer in the sensor so that the controller readjusts toward "lean" as desired and thus prevents detonation.

LEANOX

Developed and patented by Jenbacher [4-45], the LEANOX concept employs the pressure and temperature values measured after the throttle, which correspond to the energy supply at a given engine setting. In conjunction with the related NO_x values, a correlation exists between the air/fuel ratio and NO_x emission. The advantage of this concept is its independence from an engine's operating life, which has no influence on the measurement. Moreover, the controller's interpretation of this as a deviation toward "lean" equalizes any decrease of calorific value. This produces the desired enrichment of the mixture.

Ionization Sensor

Caterpillar uses an ionization sensor for its large 3600 and G-CM34 series. The basic principle is based on capturing the speed of the flame front from the spark plug to the ionization sensor mounted close to the cylinder liner. The flame speed is assigned to an NO_x emission during "calibration". The signal detected by the sensor is relatively unclear and the control system no longer functions precisely enough when combustion is very lean ($\lambda > 2.5$).

Light Emission Measurement

Research findings have demonstrated that flame radiation can be attributed to the range of the OH band for 310 nm of

NO_x emission. Thus, a distinct correlation exists. The contamination of the combustion chamber window that occurs as the running period lengthens is problematic for real engine operation. The frequent readjustment required is cost intensive and limits the system's precision and thus its application.

Cylinder Pressure Measurement

Cylinder-selective pressure measurement and the online thermodynamic analysis it enables provide an extremely elegant option. The advantage of this method is the ability to use other relevant parameters for control and monitoring, e.g. mean indicated pressure P_{mi} , maximum cylinder pressure, ignition point, duration of combustion and even detonation phenomena. This (still very expensive) concept is implemented in large marine diesel engines for the purpose of engine management [4-46]. In conjunction with inexpensive powerful computers, new sensors and methods of pressure measurement [4-47] could facilitate future use of this concept for gas engines too [4-48].

Exhaust Gas Aftertreatment

Oxidation Catalyst

TA Luft limits gas engines' CO emission to $\leq 650 \text{ mg/m}^3_n$. State-of-the-art, efficiency-optimized gas engines have raw emission of approximately 800–1,100 mg CO/m³_n. The CO primarily stems from incomplete reactions during combustion. Formaldehyde is an intermediate product of methane oxidation. Both emission components and higher hydrocarbons can be reduced greatly when the oxidation catalyst is adequately sized (space velocity and precious metal content).

Thermal Post-oxidation

Thermal post-oxidation is employed to reduce partially or unburned components in the exhaust of efficiency-optimized gas engines, which contains biogases with the aforementioned content of problem gases, which are "catalyst poisons" that render oxidation catalysts inoperable in no time. Sufficient oxygen O₂ is present in the exhaust depending on the combustion concept. However, an increase of the required oxidation temperature of $> 760^\circ\text{C}$ is necessary. Recuperative or renewable heat exchangers are used to reduce the energy required. GE Jenbacher's CLAIR system has established itself for landfill gas plants.

Literature

- 4-1 DIN EN 590 Automotive fuels - Diesel - Requirements and test methods. German version of EN 590 (2006) 3
- 4-2 Gerling, P. et al.: Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen 2005 – Kurzzstudie. Hannover: Bundesanstalt für Geowissenschaften und Rohstoffe (2007) 2 (www.bgr.bund.de)
- 4-3 Bundes-Immissionsschutzgesetz in der Fassung der Bekanntmachung vom 26. September 2002 (BGBl. I S. 3830), zuletzt geändert durch Artikel 3 des Gesetzes vom 18. Dezember 2006 (BGBl. I S. 3180), Sect. 34, 37
- 4-4 Zehnte Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes: Verordnung über die Beschaffenheit und die Auszeichnung der Qualitäten von Kraftstoffen. BGBl. I (2004) 6, p. 1342
- 4-5 European Automobile Manufacturers Association (ACEA), Japan Automobile Manufacturers Association (JAMA), Alliance of Automobile Manufacturers (Alliance), Engine Manufacturers Association (EMA), Organisation Internationale des Constructeurs d'Automobiles (OICA) (Ed.): Worldwide Fuel Charter. 4th Ed. (2006) 9
- 4-6 DIN EN 14214 Automotive fuels - Fatty acid methyl esters (FAME) for diesel engines - Requirements and test methods. German version of EN 14214 (2004) 11
- 4-7 Richtlinie 2003/30/EG des Europäischen Parlaments und des Rates vom 8. Mai 2003 zur Förderung der Verwendung von Biokraftstoffen oder anderen erneuerbaren Kraftstoffen im Verkehrssektor. EU-ABl. L 123 (2003) 5, S. 42–46
- 4-8 World Business Council for Sustainable Development (WBCSD) (Ed.): Mobility 2030 – Meeting the challenges to sustainability. The Sustainable Mobility Project – Full Report 2004. Geneva (2004) 7 (www.wbcsd.org)
- 4-9 Geringer, B.: Kurz- und mittelfristiger Einsatz von alternativen Kraftstoffen zur Senkung von Schadstoff- und Treibhausgas-Emissionen. MTZ extra: Antriebe mit Zukunft. Wiesbaden: Vieweg (2006)
- 4-10 Schindler, V.: Kraftstoffe für morgen: eine Analyse von Zusammenhängen und Handlungsoptionen. Berlin/Heidelberg: Springer (1997)
- 4-11 Hassel, E.; Wichmann, V.: Ergebnisse des Demonstrationsvorhabens Praxiseinsatz von serienmäßigen neuen rapsöltauglichen Traktoren. Abschlussveranstaltung des 100-Traktoren-Demonstrationsprojekts am 9. 11 2005 in Hannover. Universität Rostock 2005 (www.bio-kraftstoffe.info)
- 4-12 DIN V 51605 Fuels for vegetable oil compatible combustion engines - Fuel from rapeseed oil - Requirements and test methods. (2006) 7
- 4-13 Rantanen, L. et al.: NExBTL – Biodiesel fuel of the second generation. SAE Technical Papers 2005-01-3771 (www.nesteoil.com)
- 4-14 Bourillon, C. (Iogen Corporation): Meeting biofuels targets and creating a European Biofuels Industry. 4. Intern. Fachkongress "Kraftstoffe der Zukunft 2006". Berlin, November 2006
- 4-15 DIN EN 228 Automotive fuels - Unleaded petrol - Requirements and test methods. German version of EN 228, (2006) 3

- 4-16 DIN EN 15376 Automotive fuels - Ethanol as a blending component for petrol - Requirements and test methods. German version of EN 15376 (2006) 7
- 4-17 Fachagentur für Nachwachsende Rohstoffe (Ed.): Biokraftstoffe – eine vergleichende Analyse. Gülzow 2006 (www.bio-kraftstoffe.info)
- 4-18 Fachverband Biogas e.V. (Ed.): Biogas – das Multitalent für die Energiewende. Fakten im Kontext der Energiepolitik-Debatte. Freising 3/2006 (www.biogas.org)
- 4-19 Steiger, W.; Warnecke, W.; Louis, J.: Potentiale des Zusammenwirkens von modernen Kraftstoffen und künftigen Antriebskonzepten. ATZ 105 (2003) 2
- 4-20 N.N.: Biofuels in the European Union – A vision for 2030 and beyond (EUR 22066). European Commission, Office for Official Publications of the European Communities Luxembourg (2006)
- 4-21 CHOREN Industries GmbH: The Carbo-V Process (http://www.choren.com/en/biomass_to_energy/carbo-v_technology/)
- 4-22 Steiger, W.: Die Volkswagen Strategie zum hocheffizienten Antrieb. 22th Wiener Motorensymposium 2001, Vienna (4/2001)
- 4-23 Steiger, W.: Potentiale synthetischer Kraftstoffe im CCS Brennverfahren. 25th Wiener Motorensymposium 2004, Vienna (4/2001)
- 4-24 Steiger, W.: Evolution statt Revolution. Die Kraftstoff- und Antriebsstrategie von Volkswagen. Volkswagen AG Forschung Antriebe (2007)
- 4-25 Groth, K. et al.: Brennstoffe für Dieselmotoren heute und morgen: Rückstandsöle, Mischkomponenten, Alternativen. Ehningen: expert (1989)
- 4-26 Häfner, R.: Mittelschnellaufende Viertaktmotoren im Schwerölbetrieb (im Teillastdauerbetrieb). Jahrbuch der Schiffbautechnischen Gesellschaft Bd. 77. Berlin: Springer (1983)
- 4-27 Zigan, D. (Ed.): Erarbeitung von Motorkennwerten bei der Verbrennung extrem zündunwilliger Brennstoffe in Dieselmotoren im Vollast- und Teillastbereich. Schlussbericht zum Teilvorhaben MTK 03367. Krupp MaK Maschinenbau GmbH, Kiel 1988. TIB/UB Hannover: Signatur: FR 3453
- 4-28 Wachtmeister, G.; Woschni, G.; Zeilinger, K.: Einfluss hoher Druckanstiegsgeschwindigkeiten auf die Verformung der Triebwerksbauteile und die Beanspruchung des Pleuellagers. MTZ 50 (1989) 4, pp. 183–189
- 4-29 Christoph, K.; Cartellieri, W.; Pfeifer, U.: Die Bewertung der Klopffestigkeit von Kraftgasen mittels Methanzahl und deren praktische Anwendung bei Gasmotoren. MTZ 33 (1971) 10
- 4-30 Zacharias, F.: Gasmotoren. Würzburg: Vogel (2001)
- 4-31 Mooser, D.: Caterpillar High Efficiency Engine Development – G-CM34. The Institution of Diesel and Gas Turbine Engineers (IDGTE) Paper 530. The Power Engineer 6 (2002) 5
- 4-32 Hanenkamp, A.; Terbeck, S.; Köbler, S.: 32/40 PGI – Neuer Otto-Gasmotor ohne Zündkerzen: MTZ 67 (2006) 12
- 4-33 Hanenkamp, A.: Moderne Gasmotorenkonzepte – Strategien der MAN B&W Diesel AG für wachsende Gasmärkte. 4th Dessauer Gasmotoren-Konferenz (2005)
- 4-34 Wideskog, M.: The Fuel Flexible Engine. 2nd Dessauer Gasmotoren-Konferenz (2001)
- 4-35 Wärtsilä VASA Gas Diesel Motoren. Brochure Wärtsilä NSD
- 4-36 Mohr, H.: Technischer Stand und Potentiale von Diesel-Gasmotoren. Part 1: BWK 49 (1997) 3; Part 2: BWK 49 (1997) 5
- 4-37 Wagner, U.; Geiger, B.; Reiner, K.: Untersuchung von Prozessketten einer Wasserstoffenergiewirtschaft. IfE Schriftenreihe. TU München: (1994) 34
- 4-38 Vogel, C. et al.: Wasserstoff-Dieselmotor mit Direkteinspritzung, hoher Leistungsdichte und geringer Abgasemission. Part 1: MTZ 60 (1999) 10; Part 2: MTZ 60 (1999) 12; Part 3: MTZ 61 (2000) 2
- 4-39 Knorr, H.: Erdgasmotoren für Nutzfahrzeuge. Gas-Erdgas GWF 140 (1999) 7, pp. 454–459
- 4-40 Geiger, J.; Umierski, M.: Ein neues Motorkonzept für Erdgasfahrzeuge. FEV Spectrum (2002) 20
- 4-41 Pucher, H. et al.: Gasmotorentchnik. Sindelfingen: expert (1986)
- 4-42 Latsch, R.: The Swirl-Chamber-Spark-Plug: A Means of Faster, More Uniform Energy Conversion in the Spark-Ignition Engine. SAE-Paper 840455, 1994
- 4-43 Herdin, G.; Klausner, J.; Winter, E.; Weinrotter, M.; Graf, J.: Laserzündung für Gasmotoren – 6 Jahre Erfahrungen. 4. Dessauer Gasmotoren-Konferenz (2005)
- 4-44 TEM-Konzept. Brochure Deutz Power Systems
- 4-45 LEANOX-Verfahren. Brochure GE Jenbacher
- 4-46 Pucher, H. et al.: In-Betrieb-Prozessoptimierung für Dieselmotoren – Arbeitsweise und Chancen. VDI Fortschrittsberichte. Düsseldorf: VDI-Verlag 12 (1995) 239, pp. 140–158
- 4-47 Raubold, W.: Online-Ermittlung von Zünddruck und Last aus der Zylinderkopfschraubenkraft. Diss. TU Berlin (1997)
- 4-48 Eggers, J.; Greve, M.: Motormanagement mit integrierter Zylinderdruckauswertung. 5. Dessauer Gasmotoren-Konferenz (2007)